

Colliders and their Window into the Universe

The Past, Present, and Future

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Science Engineering and Technology Colloquium

February 19, 2013

Wherefore particle physics?

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~~Playing with really cool toys~~

Wherefore particle physics?

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Answering the big questions

Wherefore particle physics?

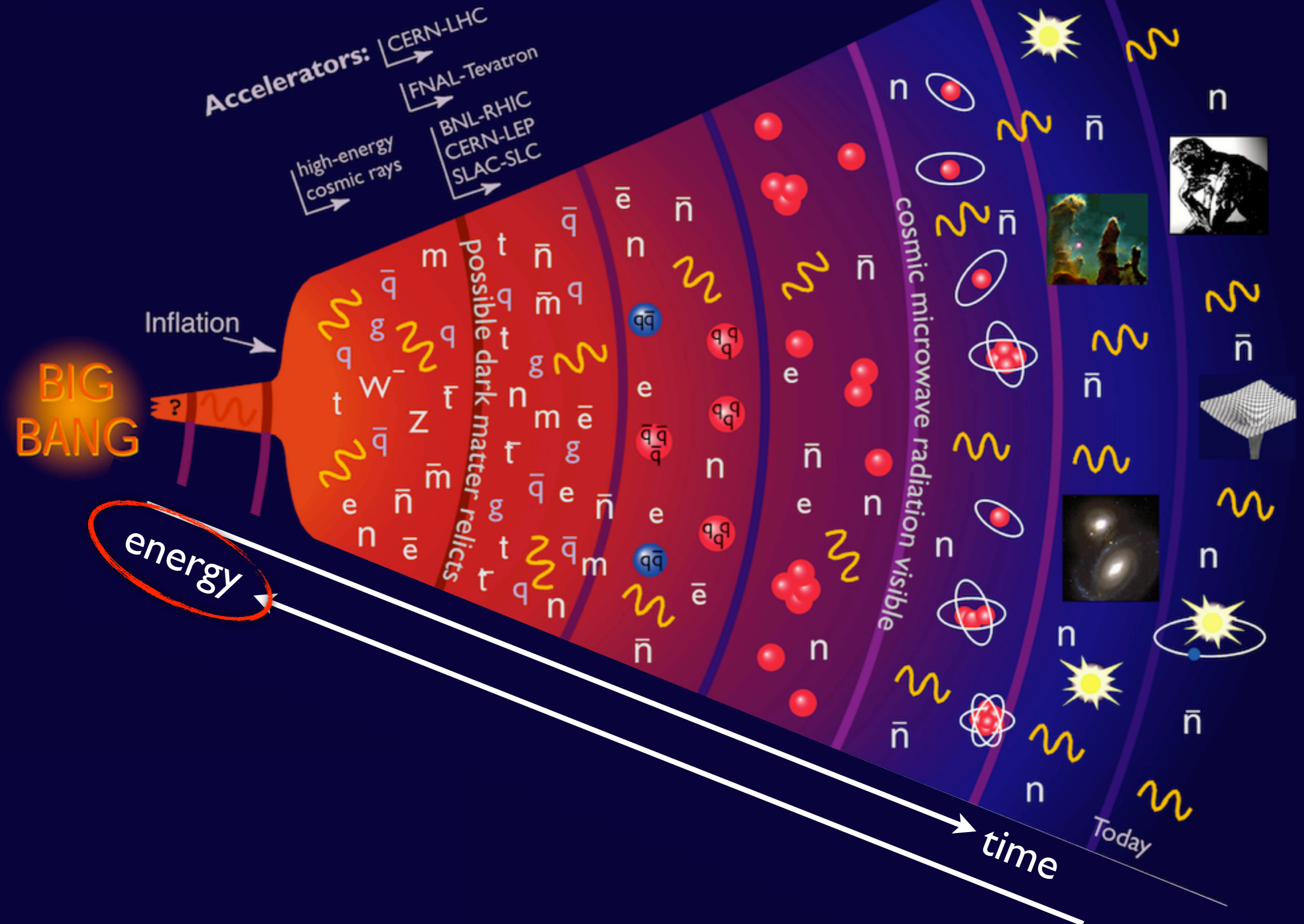
~~Playing with really cool toys~~

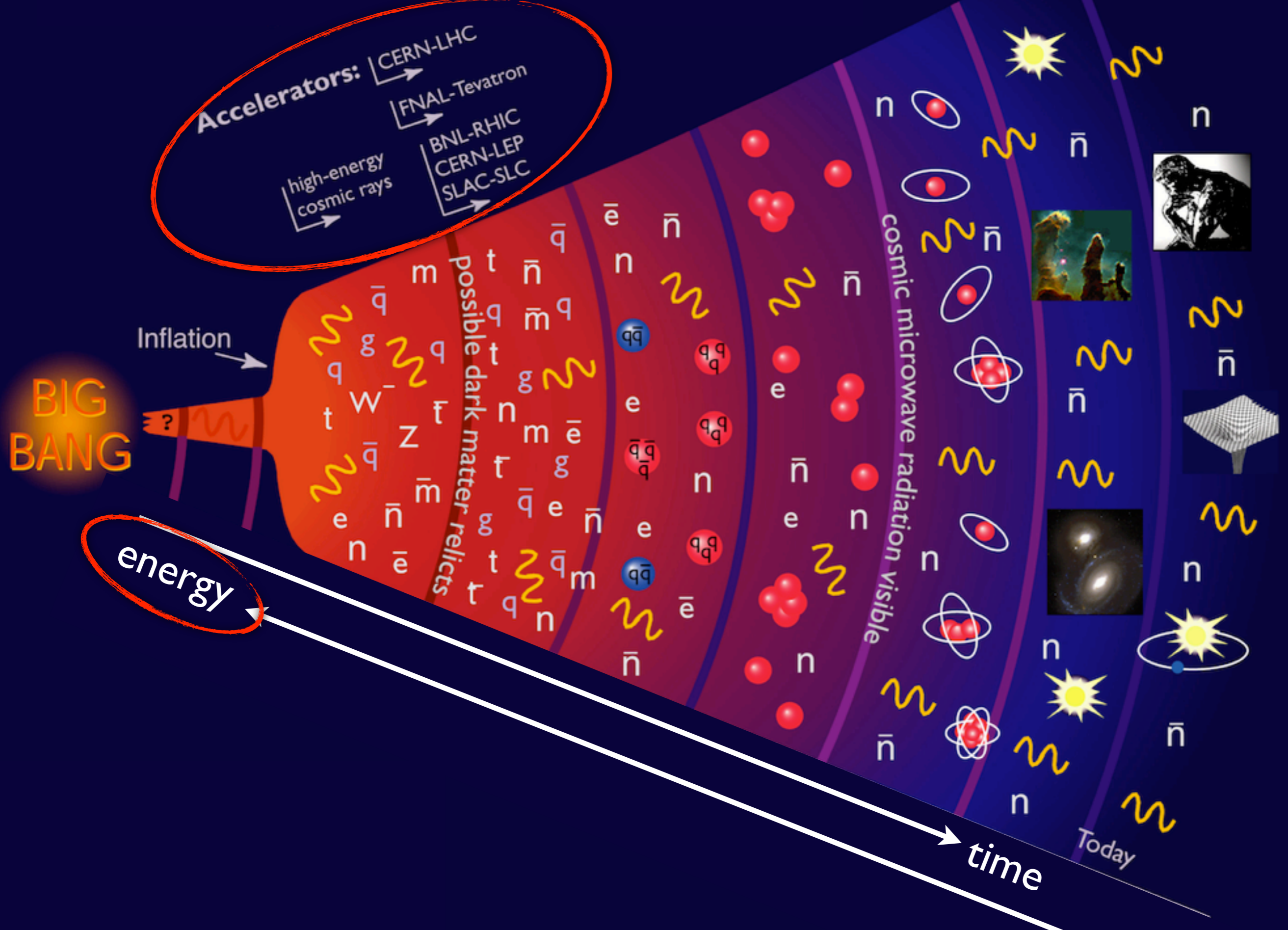
Answering the big questions

What is the universe made of?

What holds it all together?

Where did we come from?





Accelerators:

- CERN-LHC
- FNAL-Tevatron
- BNL-RHIC
- CERN-LEP
- SLAC-SLC
- high-energy cosmic rays

BIG BANG

Inflation

possible dark matter relicts

cosmic microwave radiation visible

Today

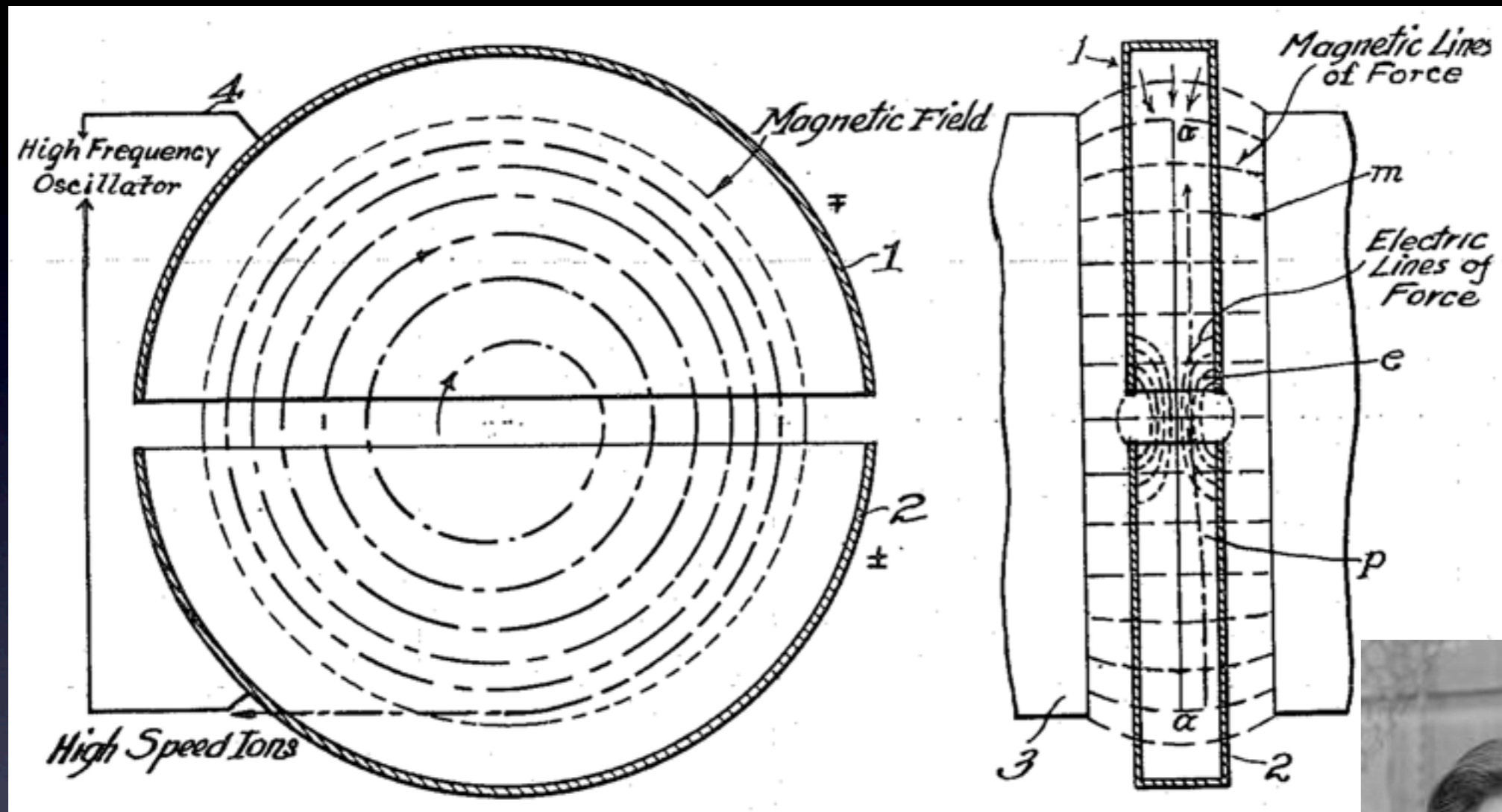
$$E=mc^2$$

- **Mass-energy equivalence**
- Colliding particles at energy E can produce particles of mass up to m
- Rinse, lather, repeat
 1. Discover new particles (need enough of them)
 2. Measure their properties (need a lot of them)
- ➡ I will provide a more detailed example of both
- $c=1 \rightarrow E=m$
 - $m_{\text{electron}} \sim 0.5 \text{ MeV}, m_{\text{proton}} \sim 1 \text{ GeV}$

Accelerators

- Oscillating **electric fields** to accelerate a charged particle
 - $\mathbf{F} = q\mathbf{E}$ & $\mathbf{F} = m\mathbf{a} : \mathbf{a} = q\mathbf{E}/m$
- Use **magnets** to steer particles
- Collide two beams of particles into each other:
particle collider
- Measure momenta of (stable) decay products:
particle detector

The Cyclotron



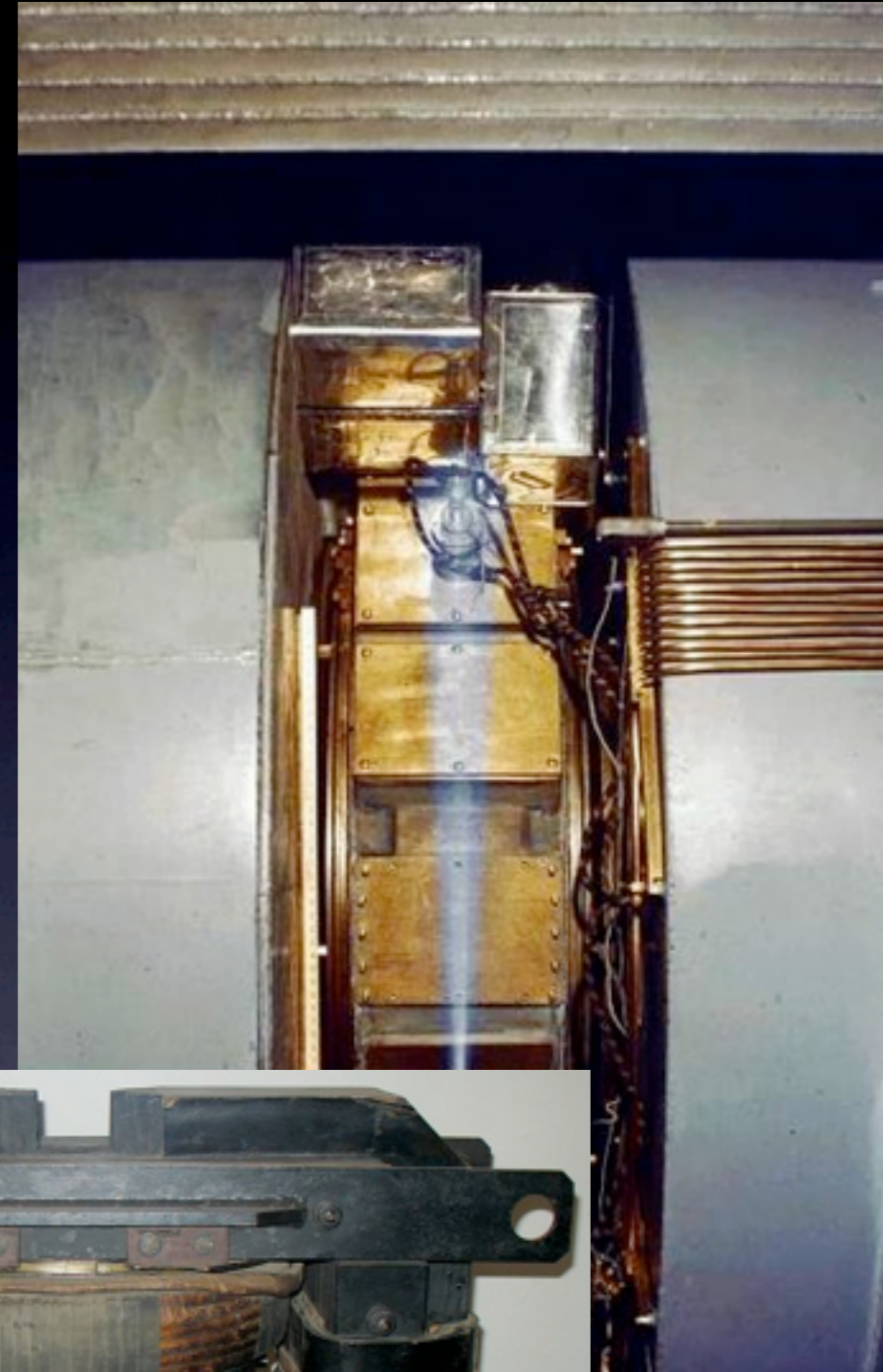
Ernest Lawrence

Nobel Prize in Physics (1939)

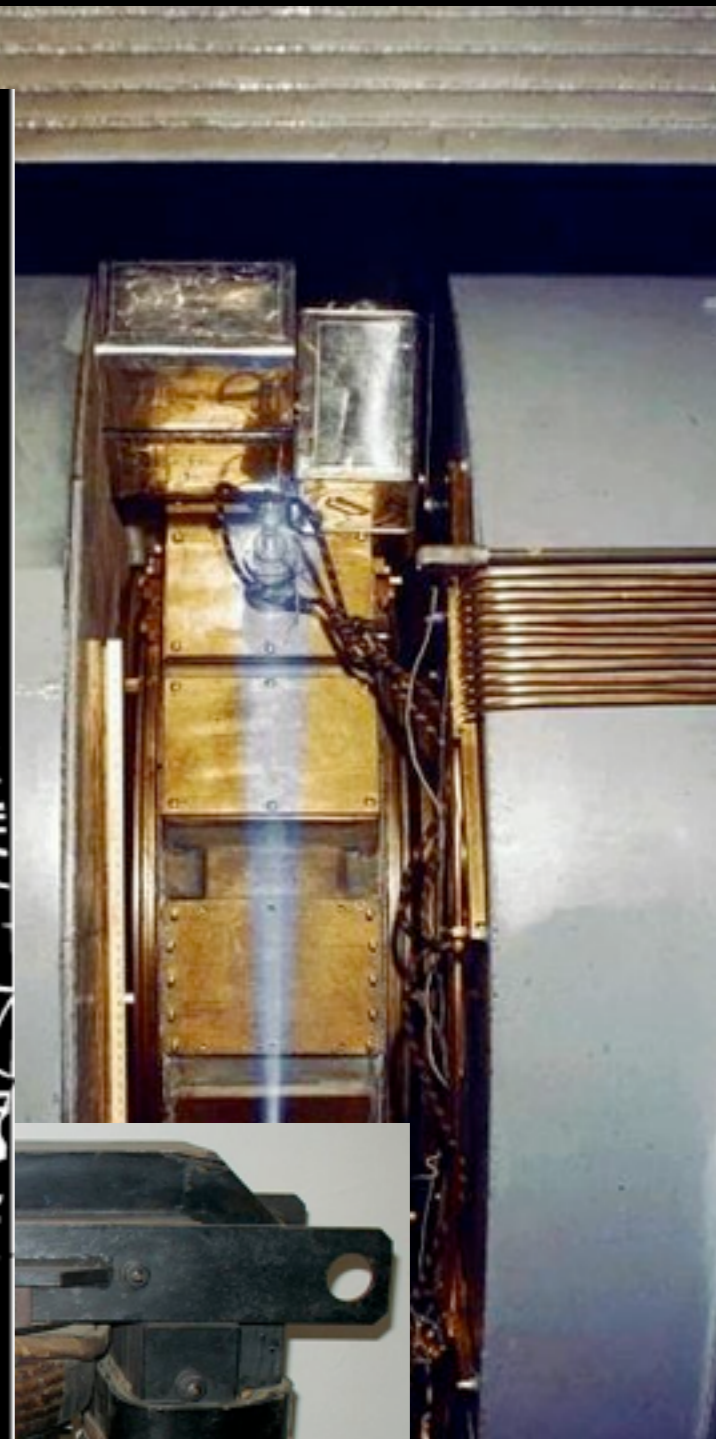
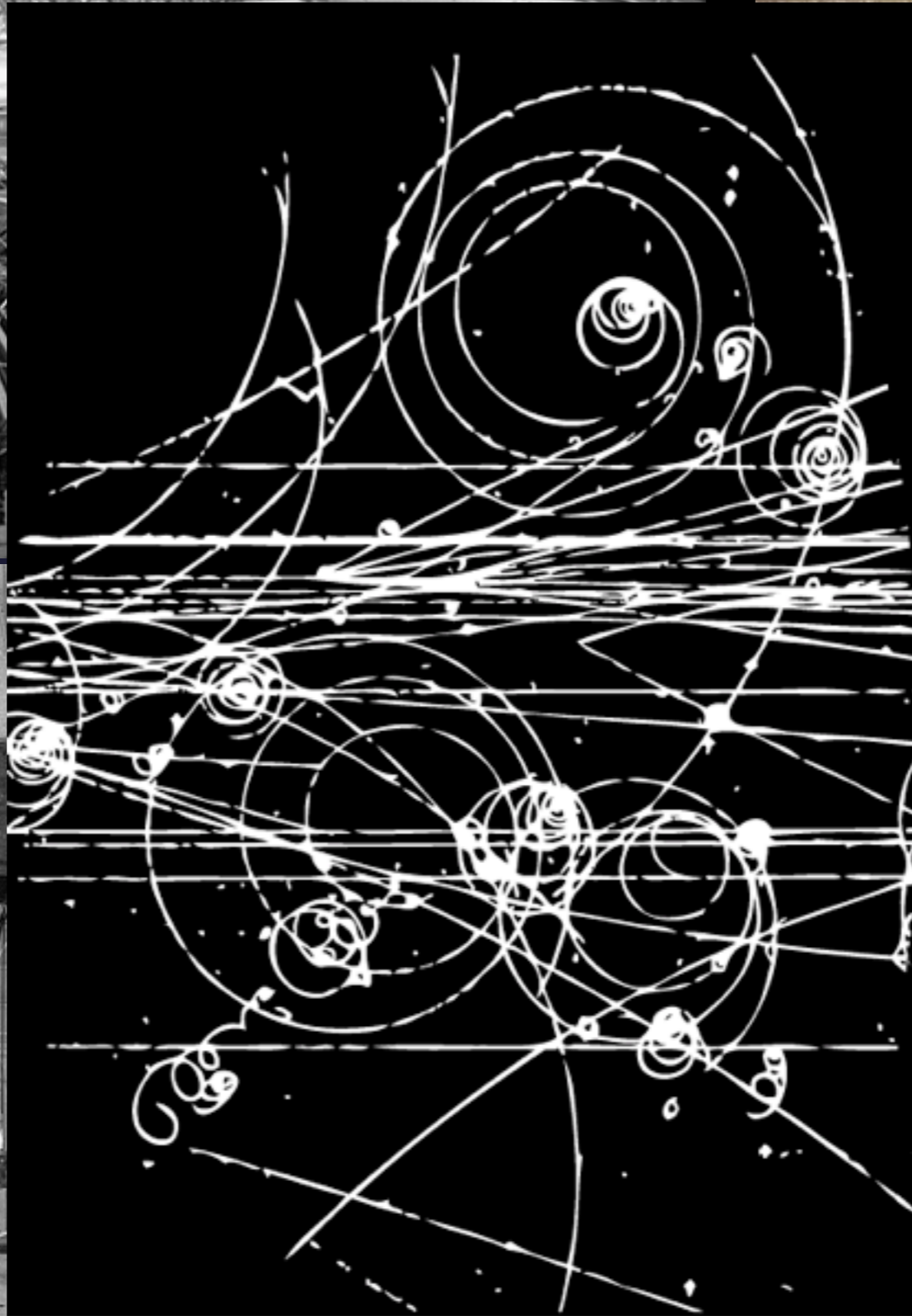
Accelerated protons to 80 keV (1% the speed of light)



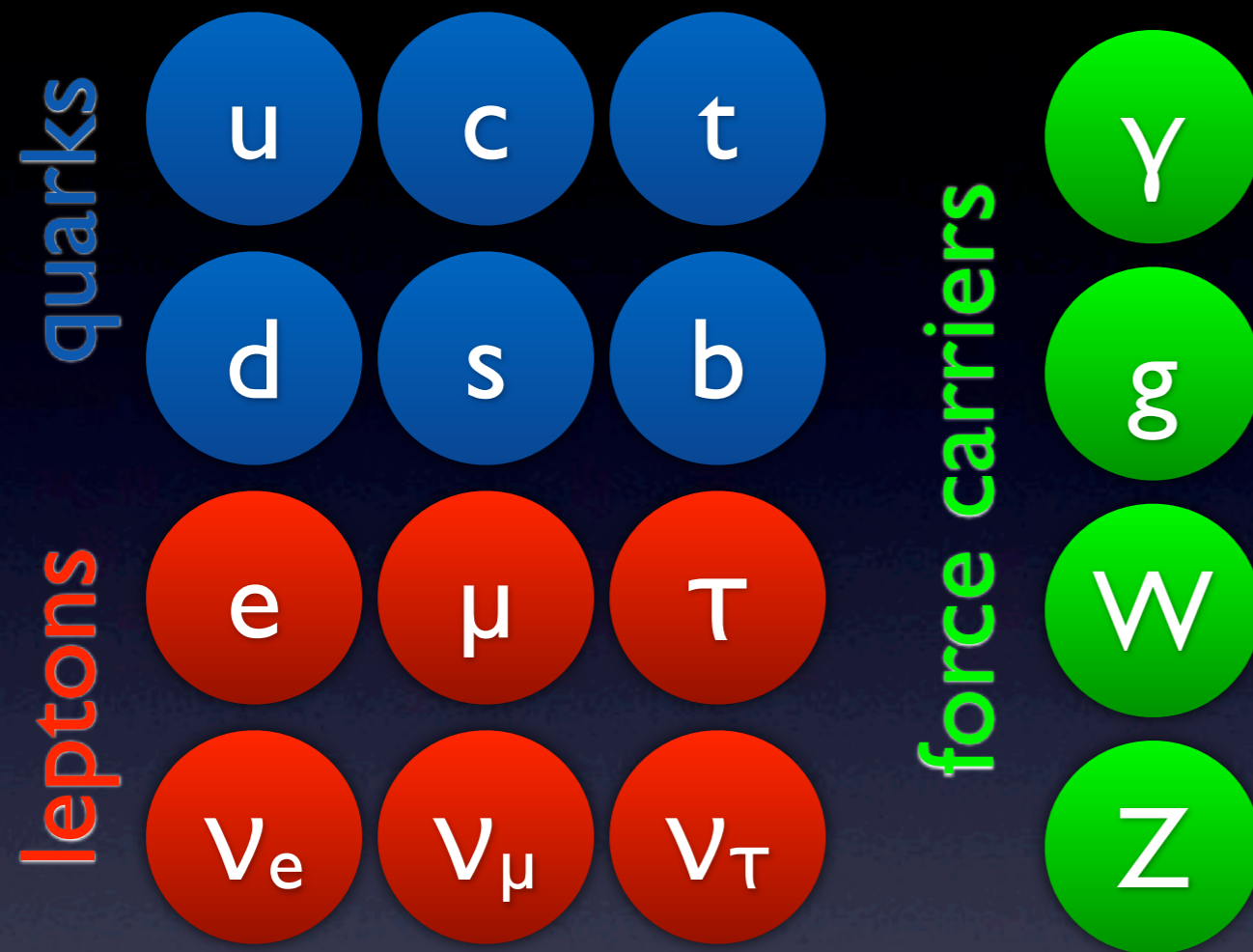
Accelerators Everywhere



Accelerators Everywhere



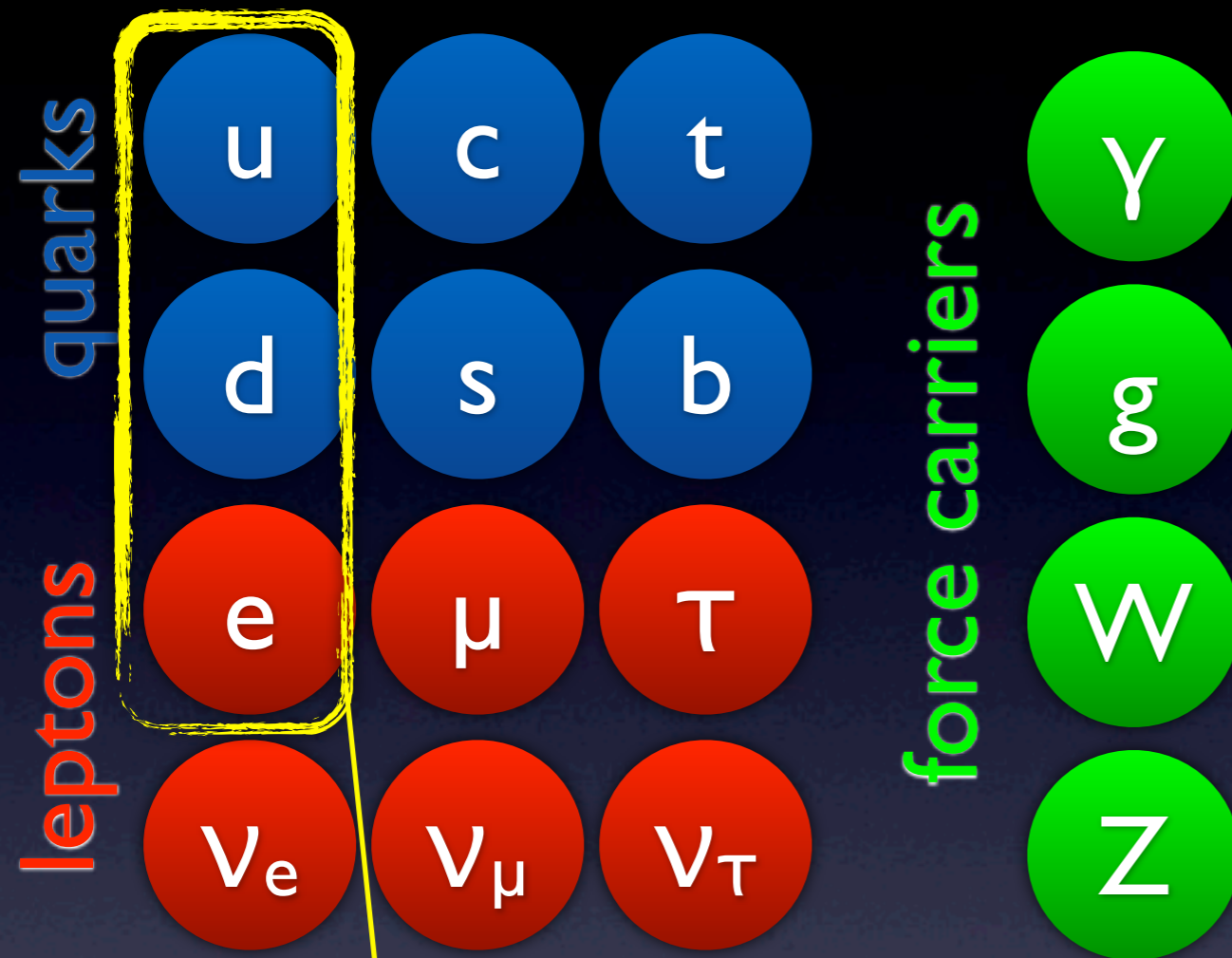
The Standard Model (1960s)



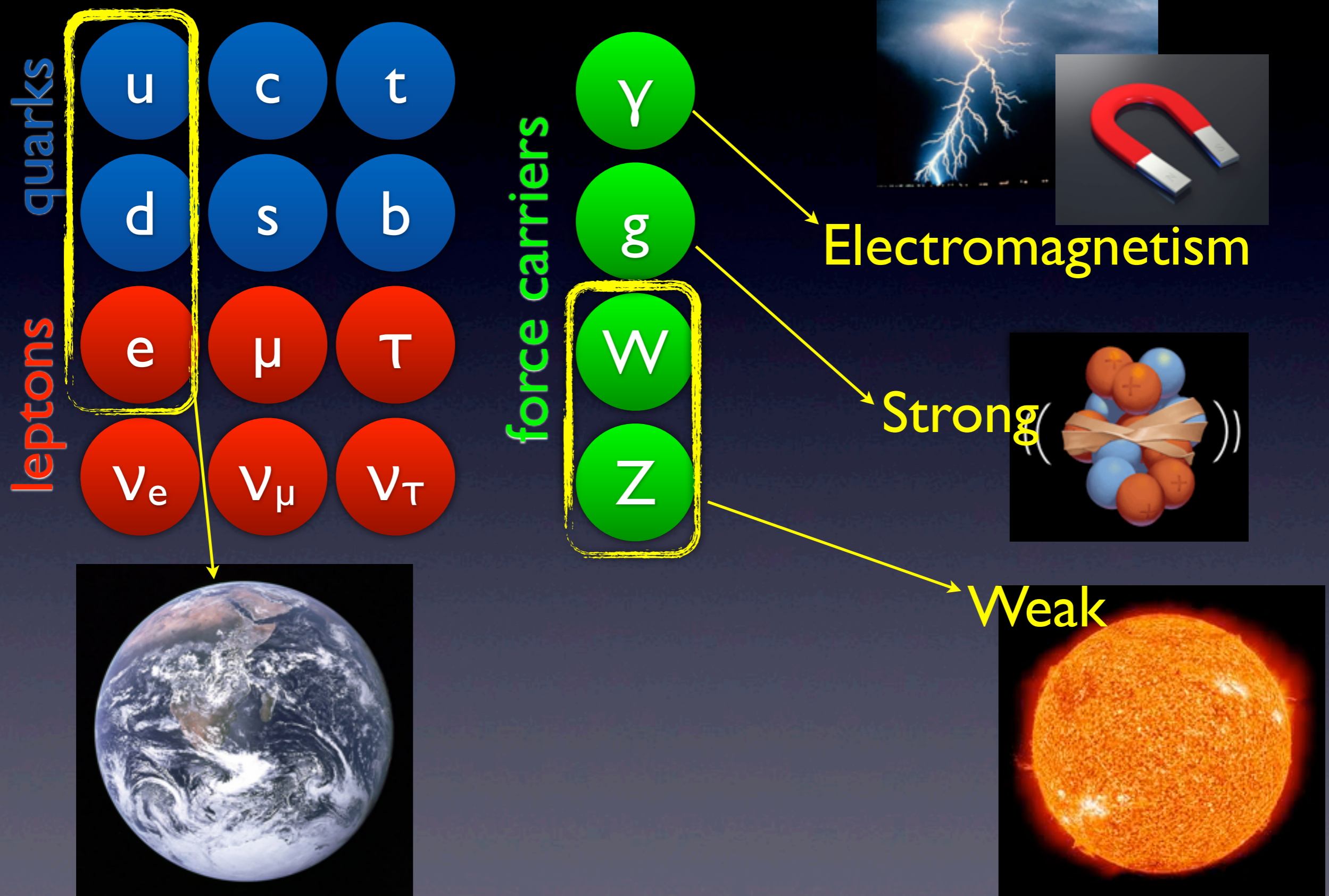
Fermions:
spin-1/2

Bosons:
spin-1

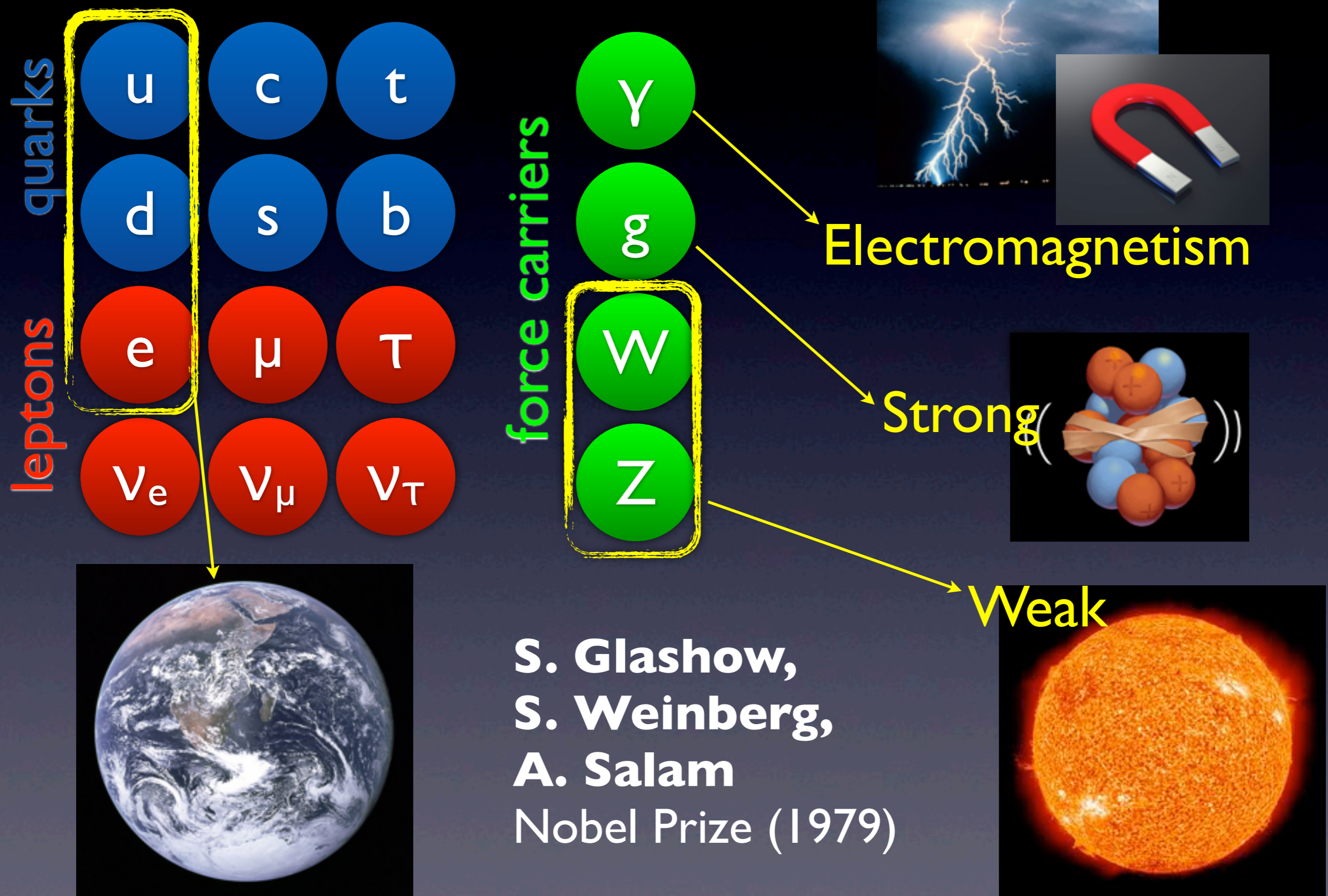
The Standard Model (1960s)



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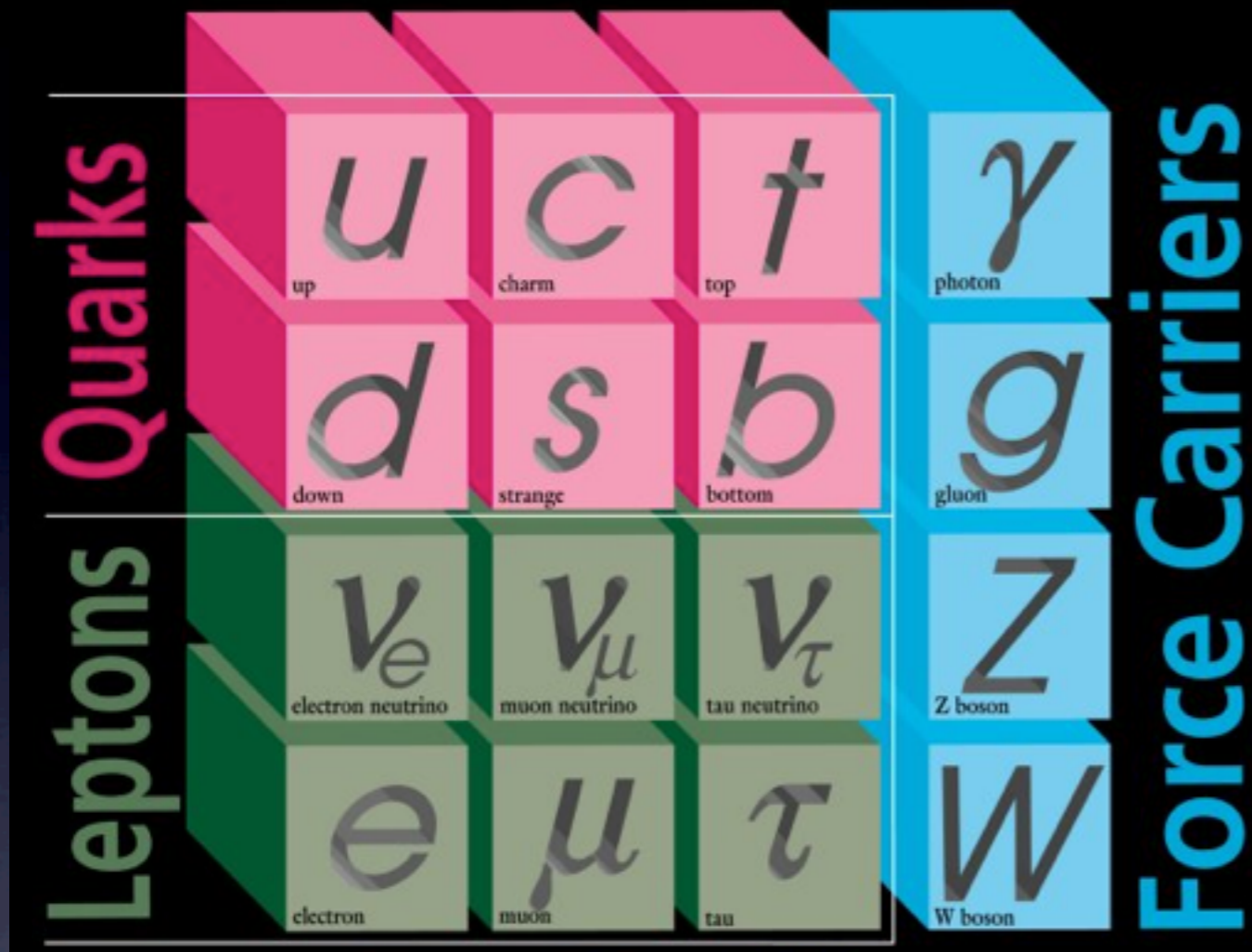


The Standard Model (1960s)



The 21st Century

The 21st Century



The 21st Century

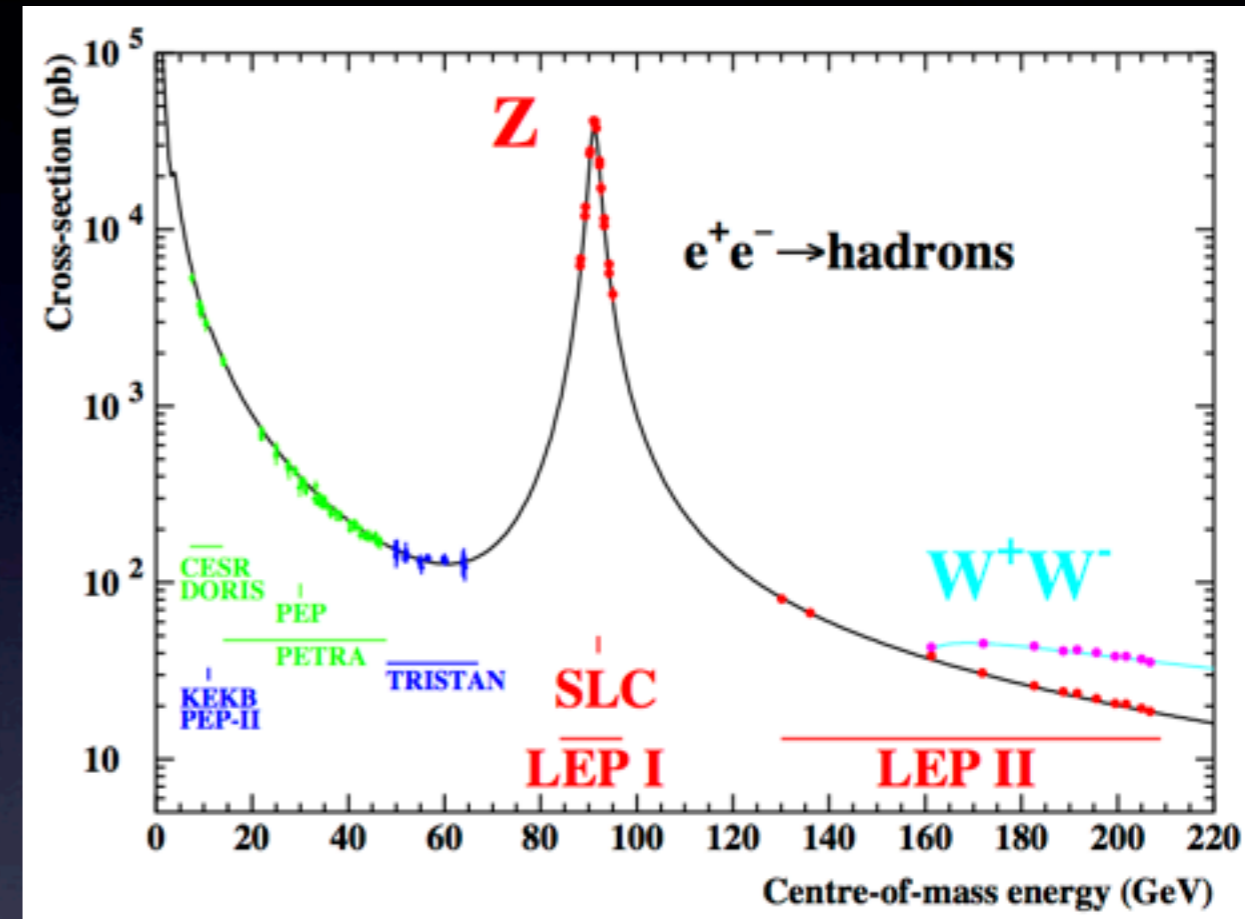


- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1978@DESY
- W and Z boson: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL

The 21st Century



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Precision measurements of particle properties agree with standard model predictions

But...

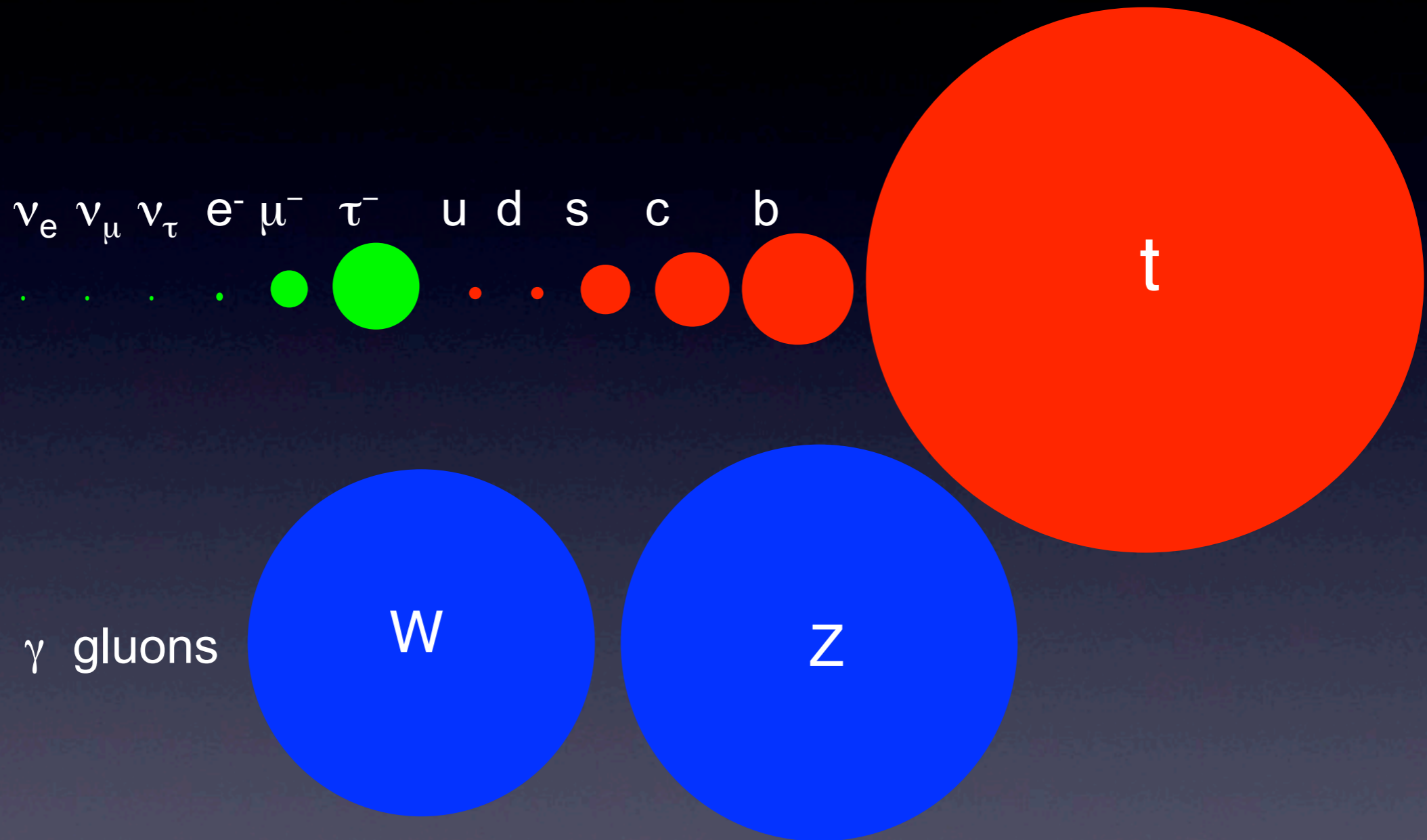
Many questions remain
such as..

But...

Many questions remain
such as..

Why do particles have mass?

But...



(Mass proportional to area shown: proton mass = ●)

The Higgs* Mechanism

No Higgs Field

With the Higgs Field

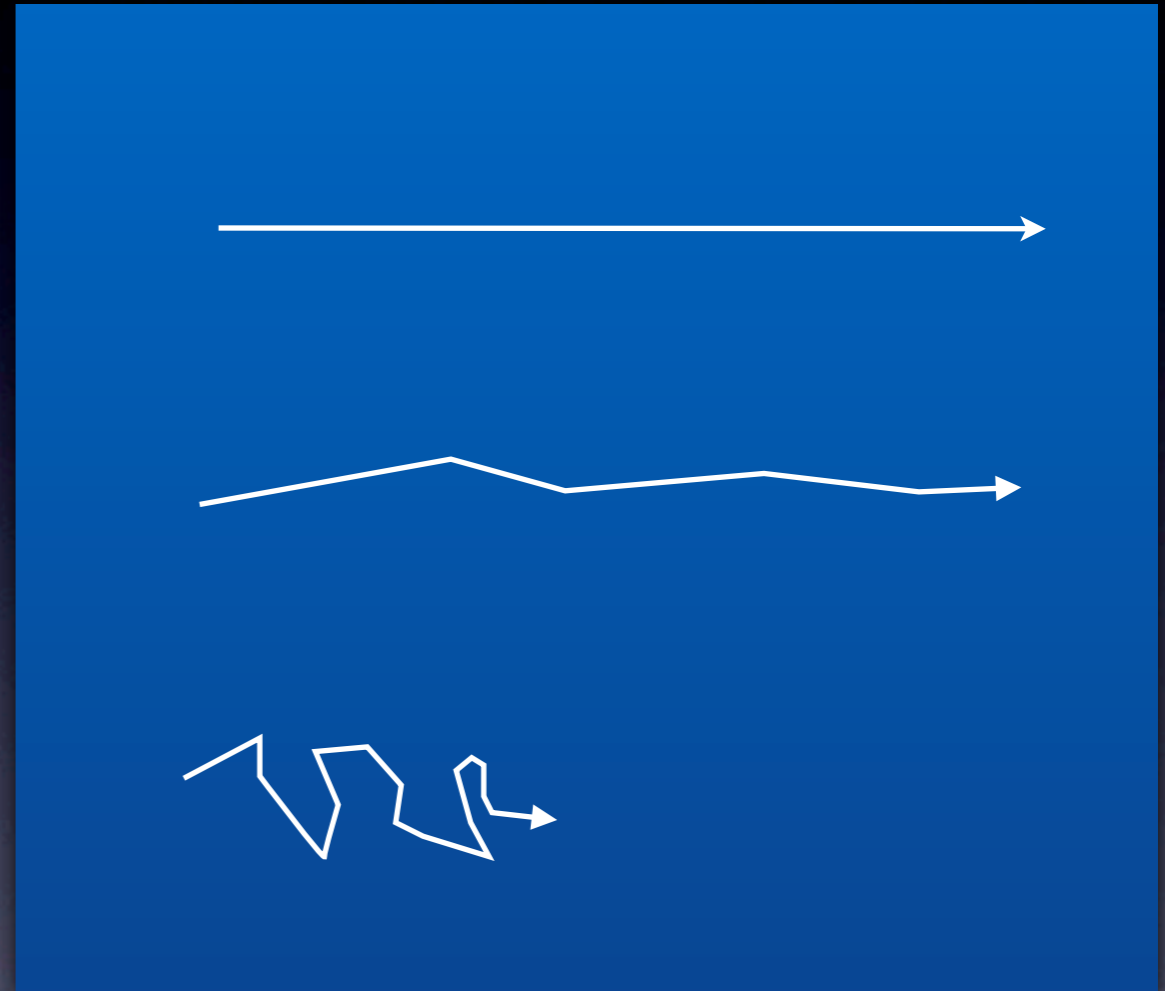
Photon
 $m=0$ MeV



Electron
 $m=0.511$ MeV



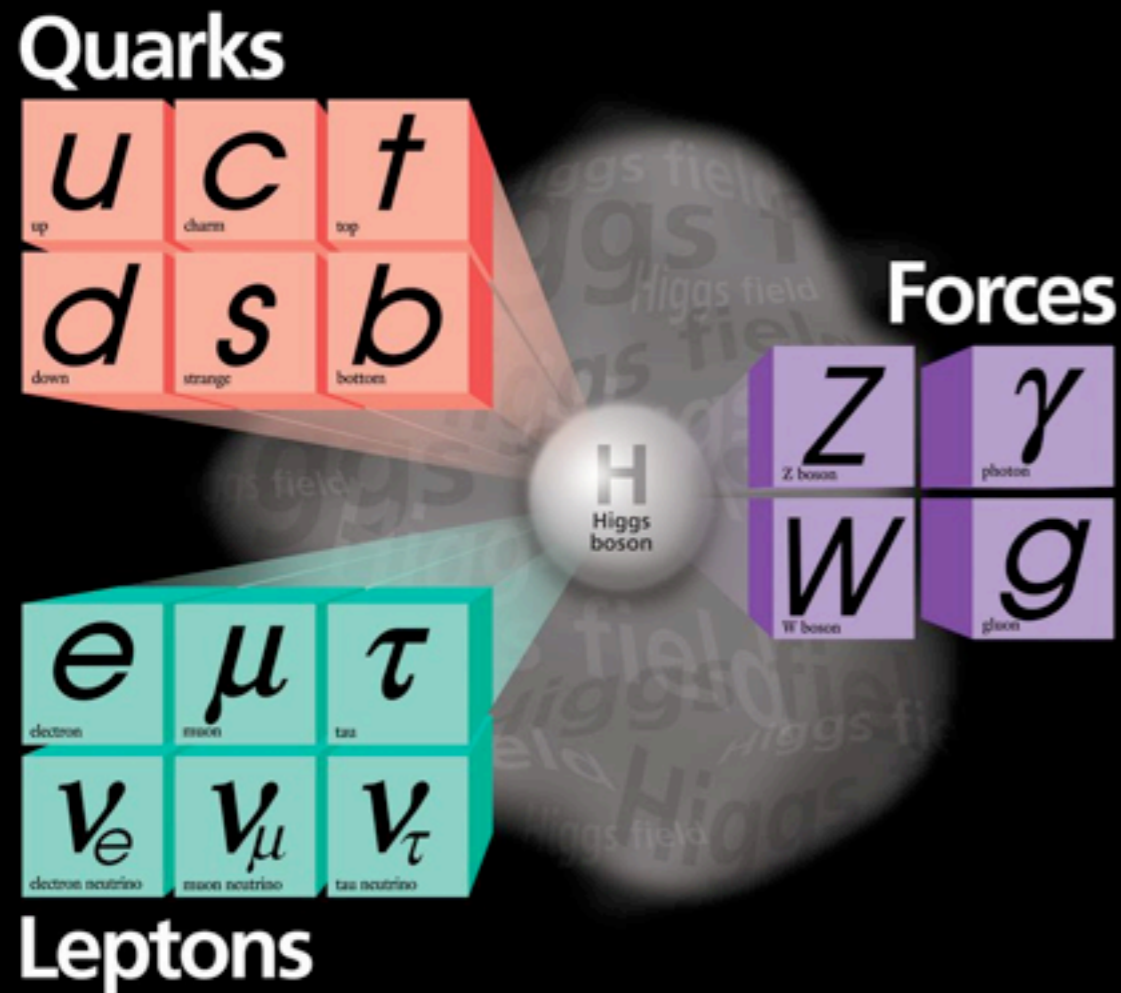
Top quark
 $m=173.180$ MeV



- Field that permeates the universe
- Interaction corresponds to mass

*[Brout, Englert]; [Higgs]; [Guralnik, Hagen, Kibble]

The Higgs Boson

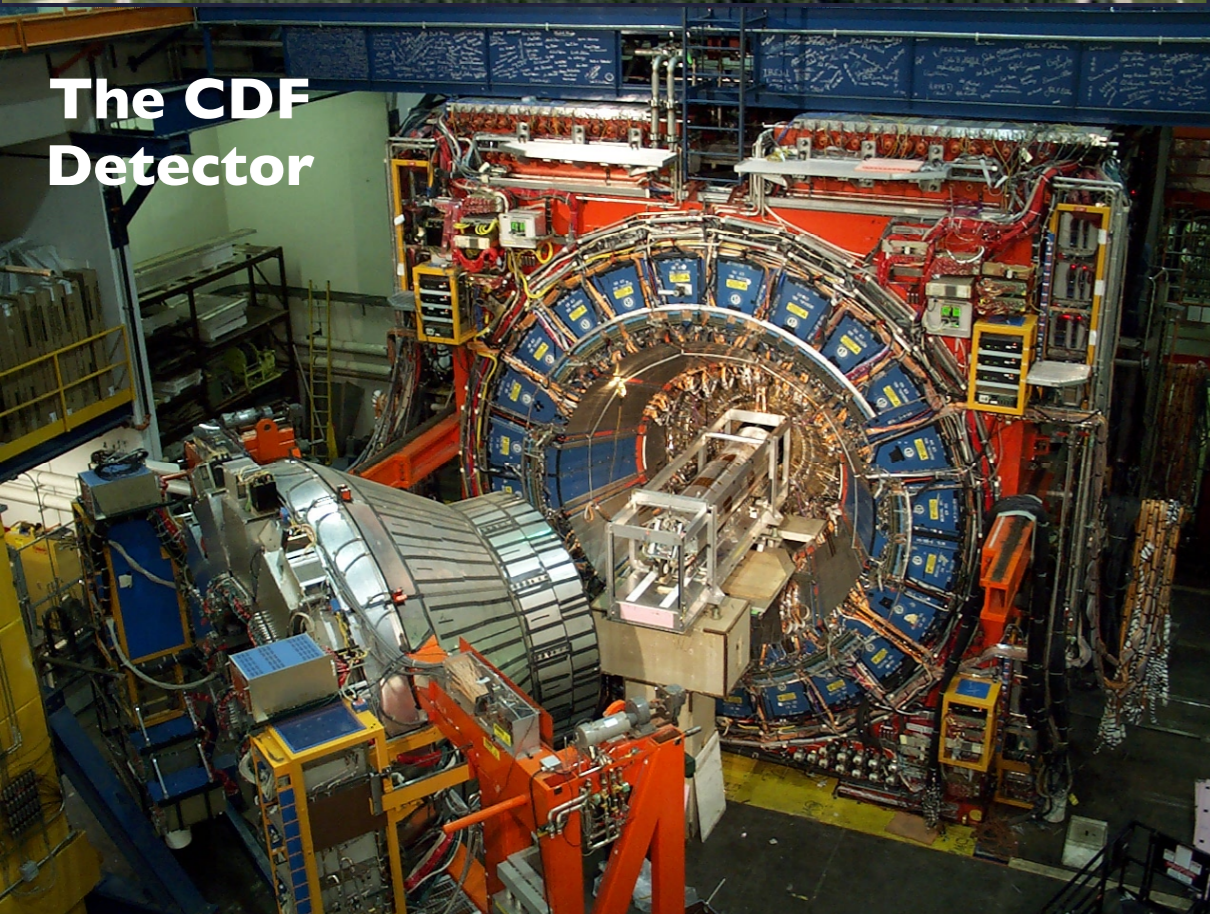


- Peter Higgs postulates a particle associated with the Higgs Field
- The Higgs Boson (spin 0)
- “The God Particle” (L. Lederman)
- Searches throughout the latter half of the 20th century yielded no evidence

Predicting the Higgs Boson's Mass

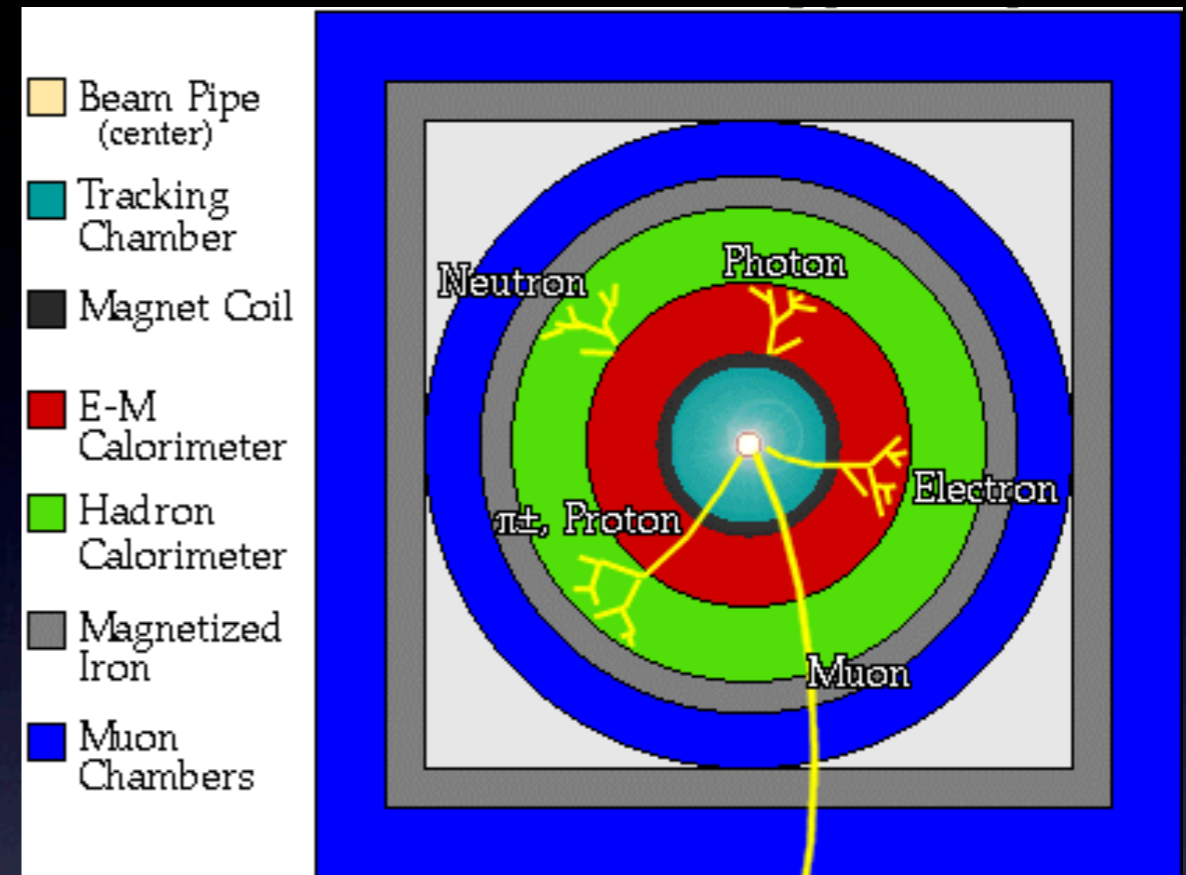
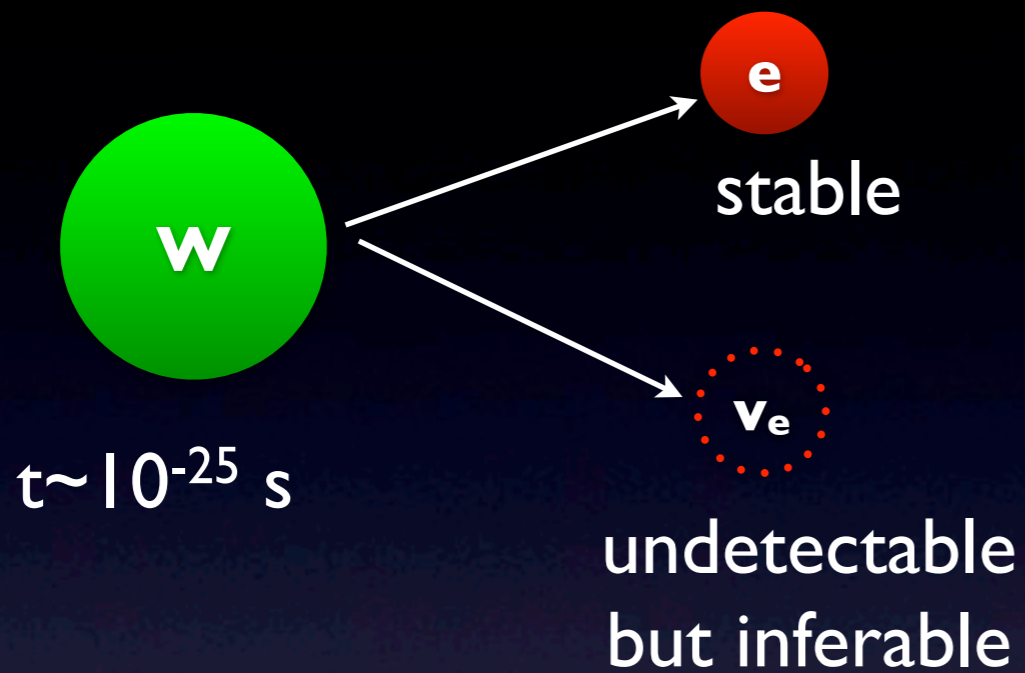
- Direct searches up to 2006 exclude $m_H < 114$ GeV
- Standard Model predicts the mass of the Higgs boson in terms of all other measured SM parameters
 - In particular, the mass of the **W boson**
- As of 2006, $m_W = 80.403 \pm 0.029$ GeV (0.04%)
 - Predicts $m_H < 186$ GeV

The Fermilab Tevatron



- Proton-antiproton collider at up to 980 GeV per beam
 - Operated from 1992-1996 at 1.8 TeV, 2001-2011 at 1.96 TeV
- First ever superconducting particle collider
 - ~4T superconducting magnets
- Two detector experiments: **CDF** and **D0**
 - ~600 physicists each

“Seeing” with Detectors



- Layered detectors measure energy deposition of particles
- Rely on “reconstructing” parent particle from stable decay products

Calibrating Energy Measurements

Calibrating Energy Measurements

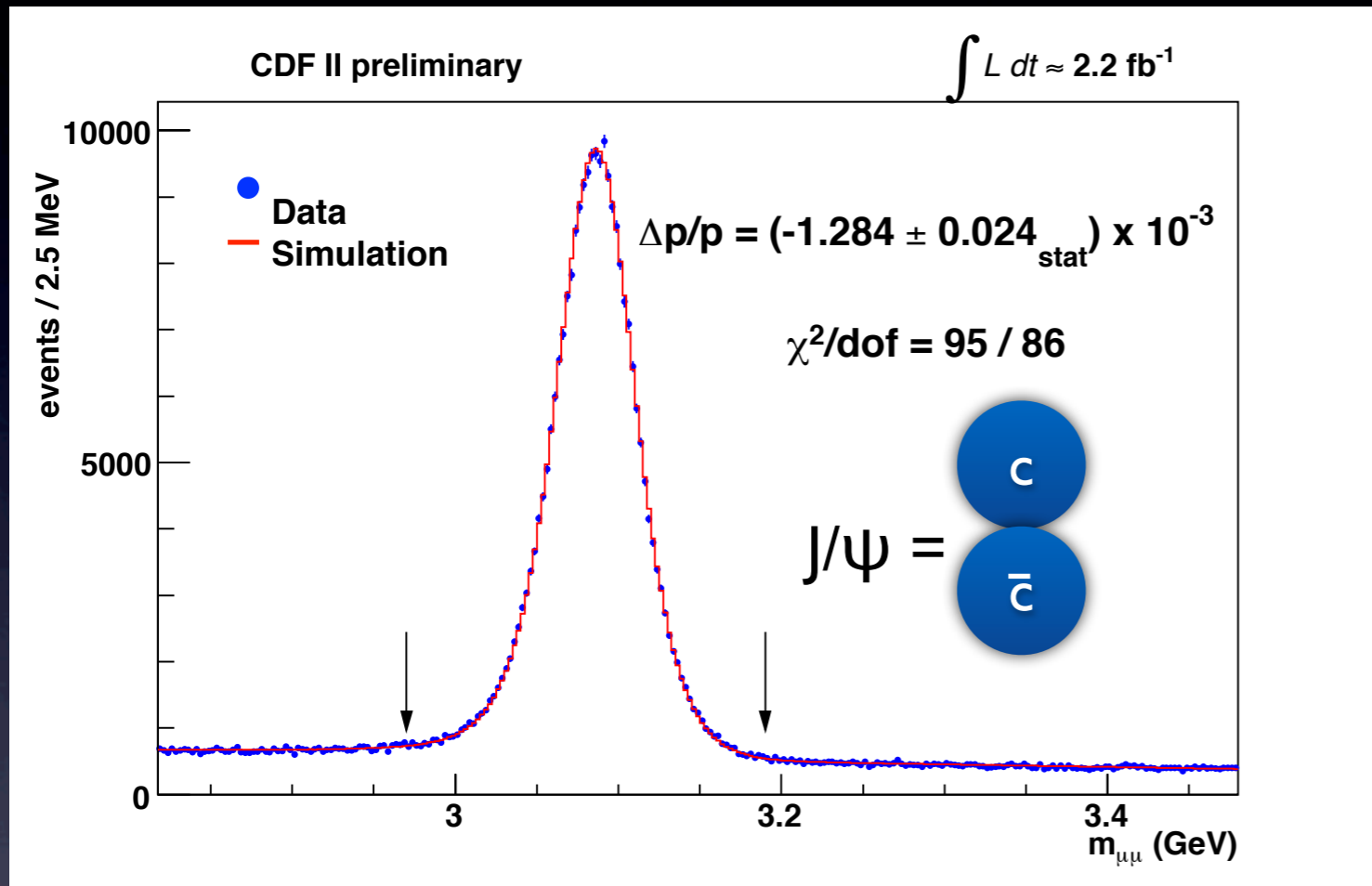


Calibrating Energy Measurements



Thermometer: CDF Detector
Ice Water: Previously well-measured particles

Calibrating Energy Measurements

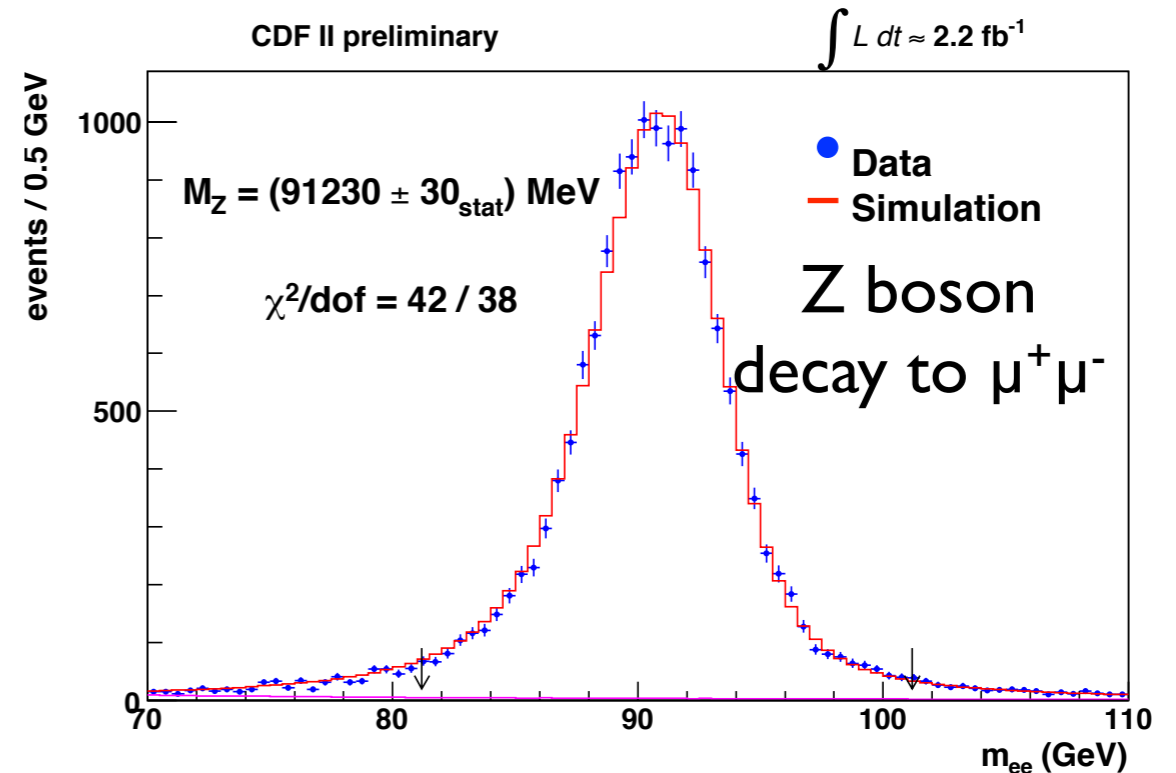
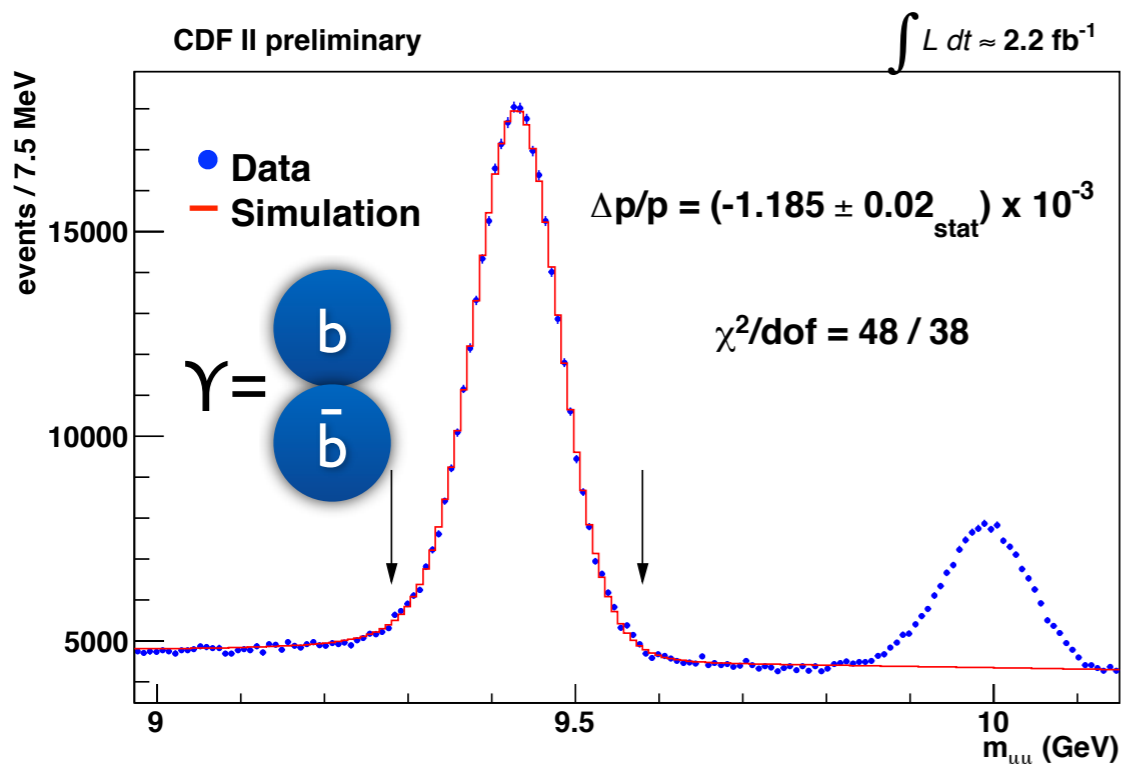
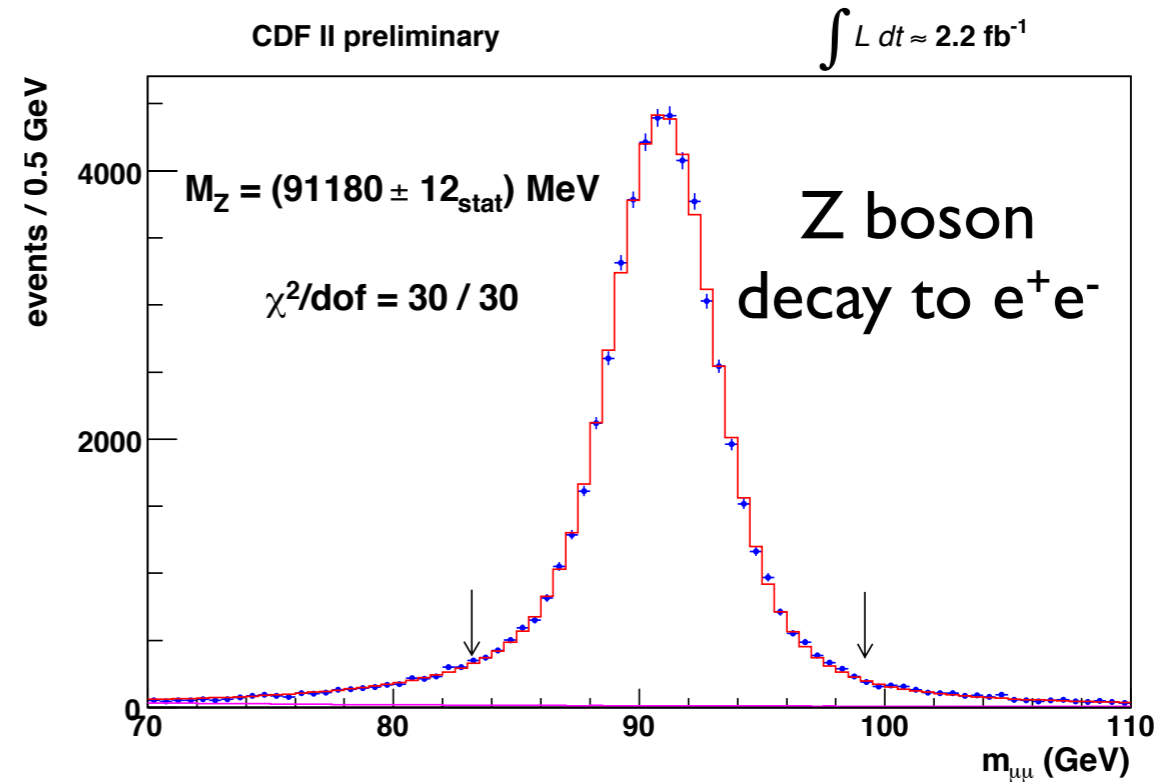
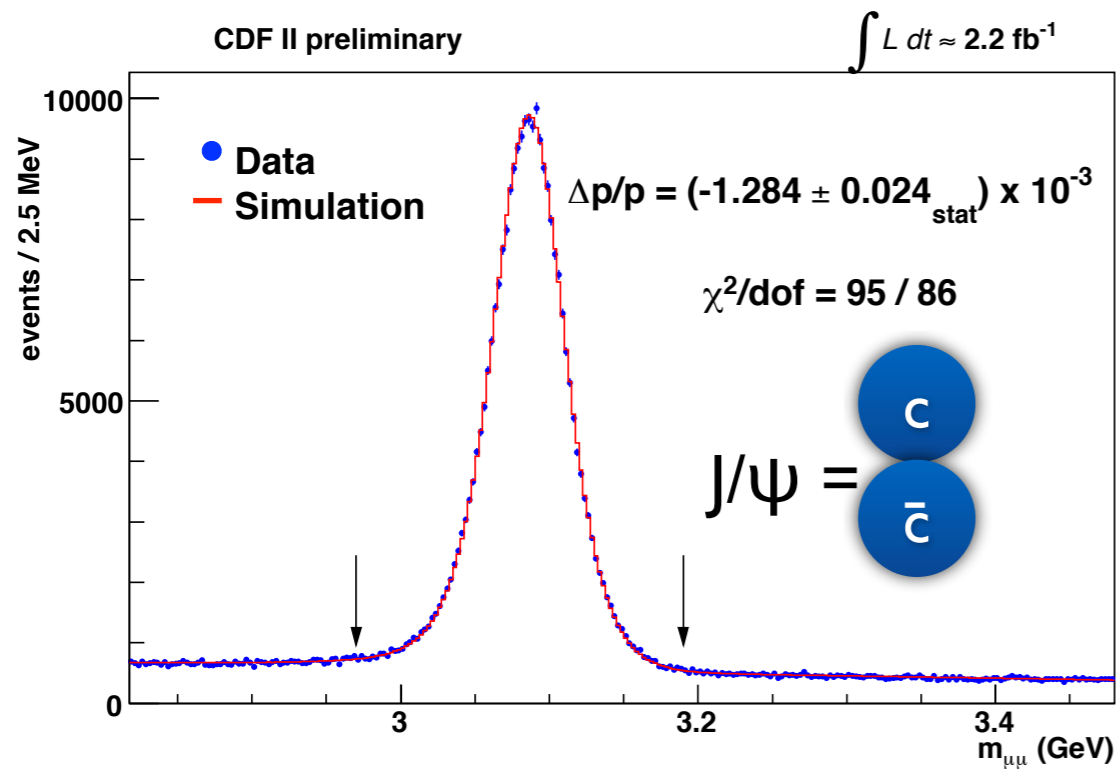


J/ψ mass measured from
other experiments
 $m_{J/\psi} = 3096.916 \pm 0.011 \text{ MeV}$

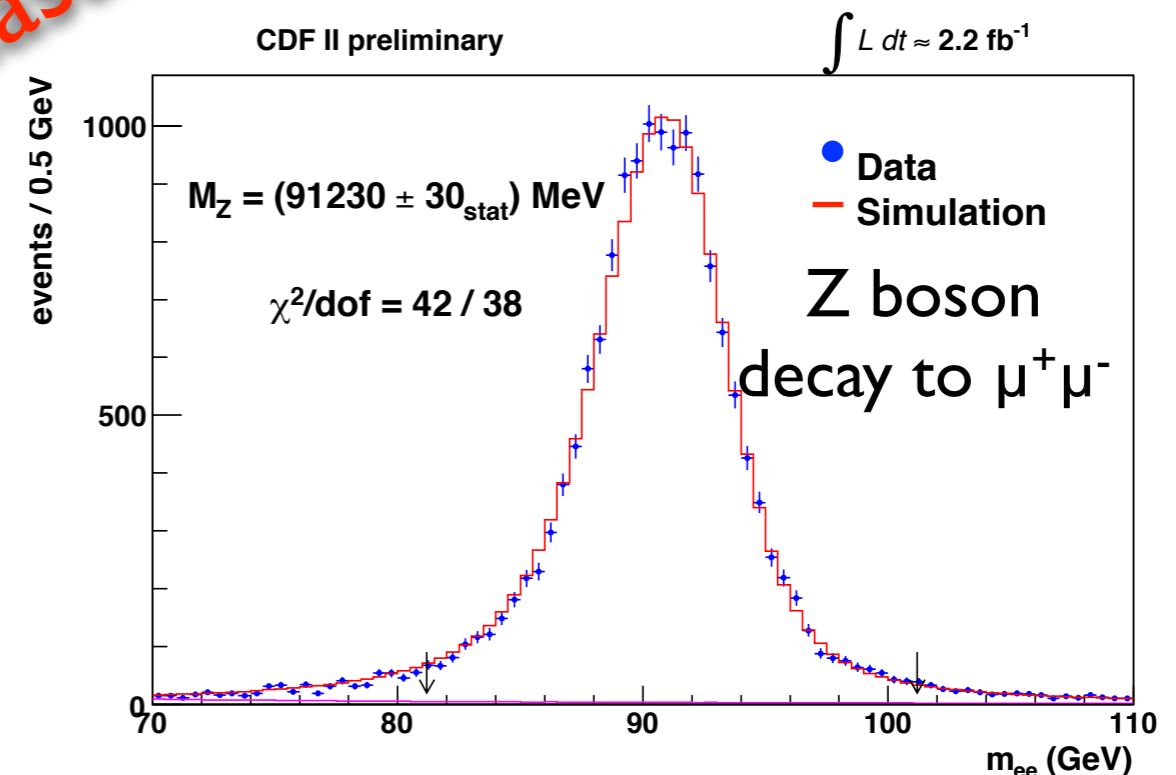
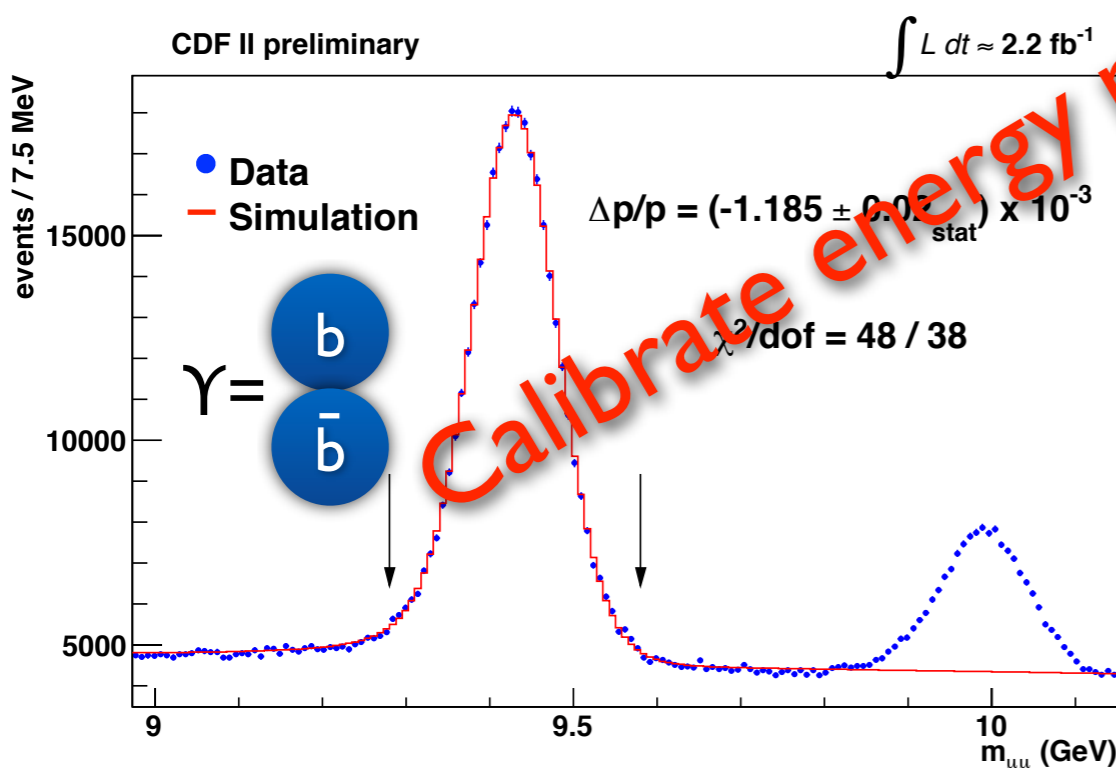
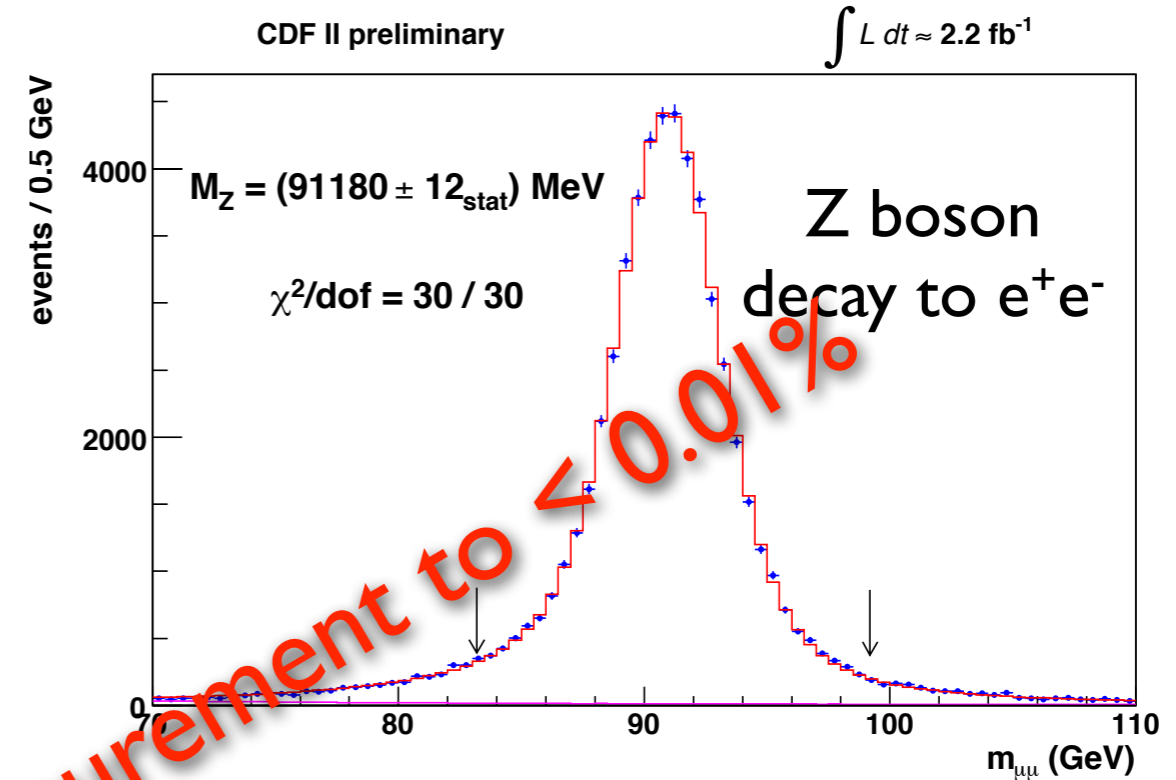
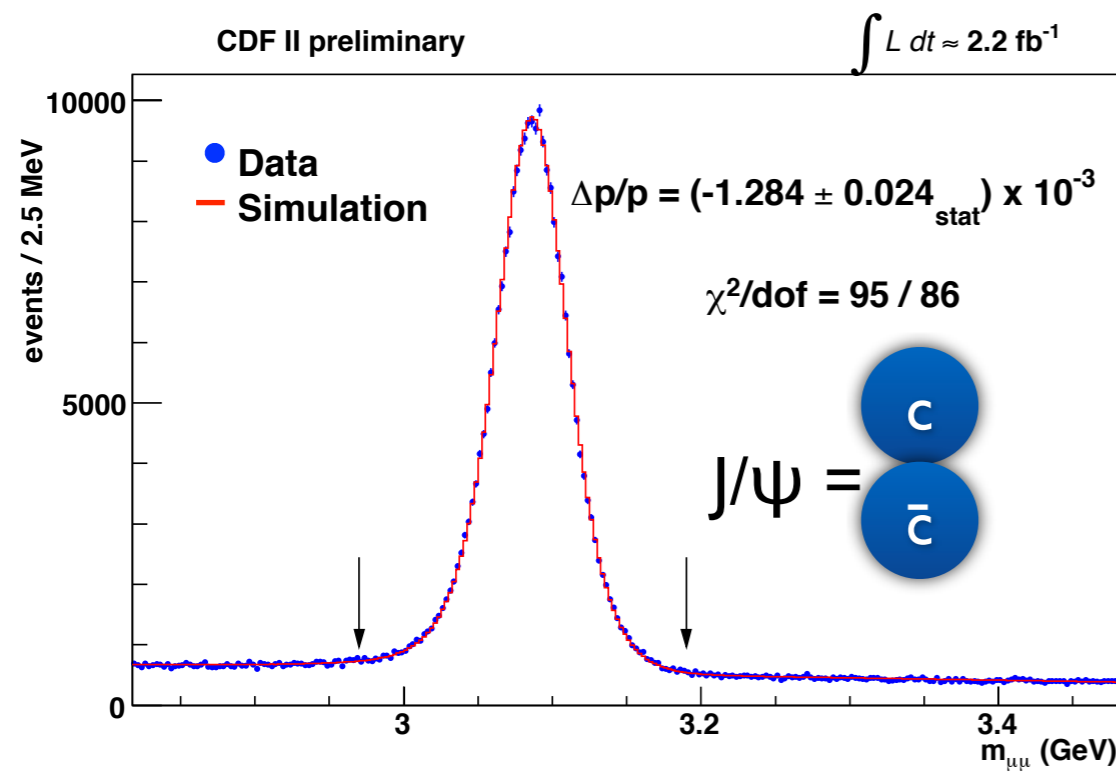
Turn measurement of J/ψ at
CDF into measurement of
correction needed to
obtain $m_{J/\psi}$

Calibrating Energy Measurements

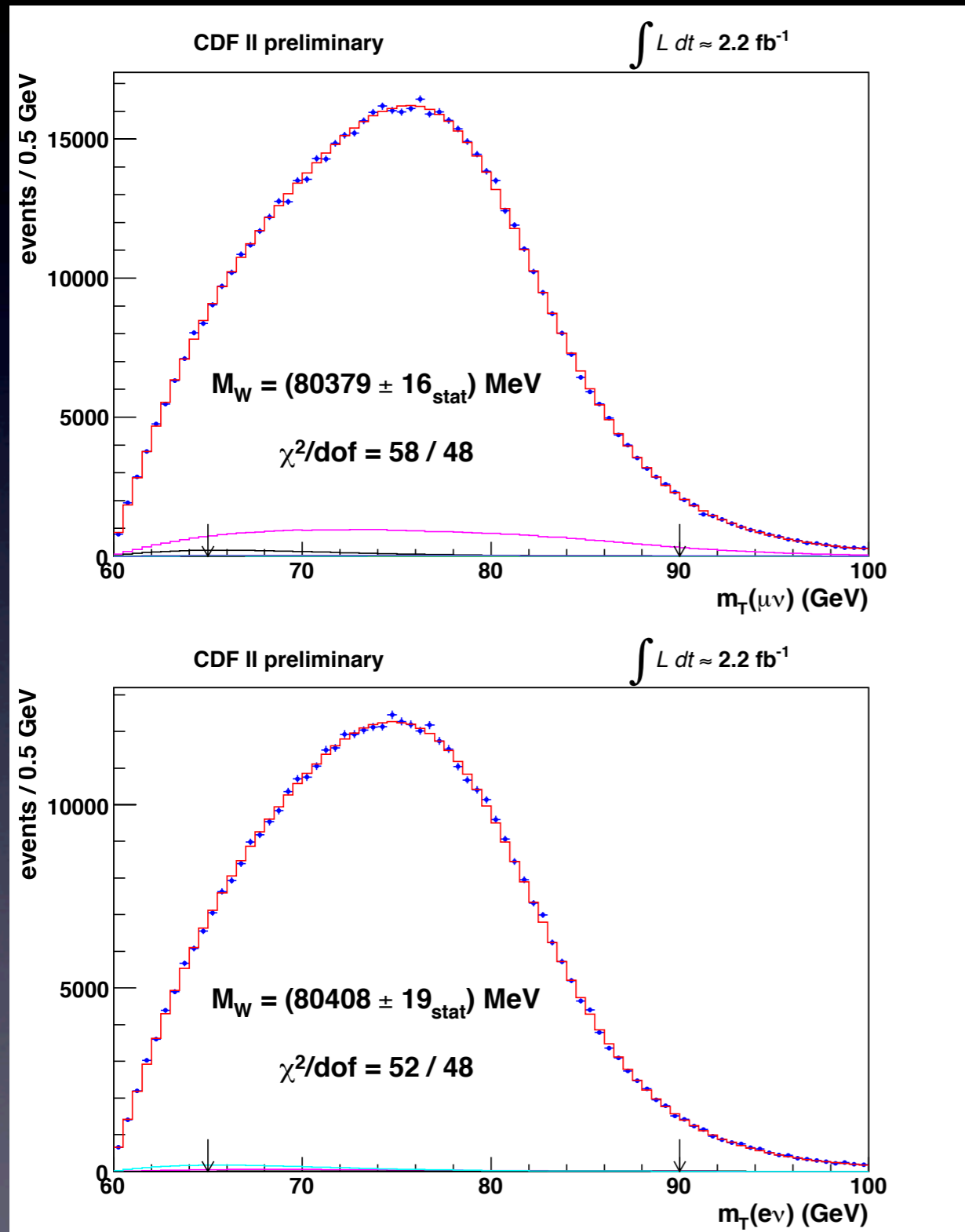
Calibrating Energy Measurements



Calibrating Energy Measurements



Measured W Boson Mass



Using ~ 1 million W boson decays

$$m_W = 80.387 \pm 0.019 \text{ GeV}$$

Combined with measurements
from other experiments

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

Science News

... from universities, journals, and other research organizations

World's Best Measurement of W Boson Mass Points to Higgs Mass and Tests Standard Model

Good news for Higgs: Physicists pinpoint W boson

Work helps understand exotic particles, narrows range of possible 'God particle' energies

Synopsis: W Marks the Spot



Precise Measurement of the W Boson Mass
 T. Aaltonen et al. (CDF Collaboration)
 Phys. Rev. Lett. **108**, 151801
 Published April 12, 2012

Measurement of the W Boson Mass
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LIFE AND PHYSICS JON BUTTERWORTH

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Tevatron results: W marks the spot

It's often said that without a Higgs boson, the standard model of particle physics is in deep trouble. As [Bo Jayatilaka](#) writes, if the ellipse didn't overlap with this line, it already would be...

Physicists Pinpoint W Boson, Narrow Search for Higgs

BY ADAM MANN 02.23.12 5:01 PM



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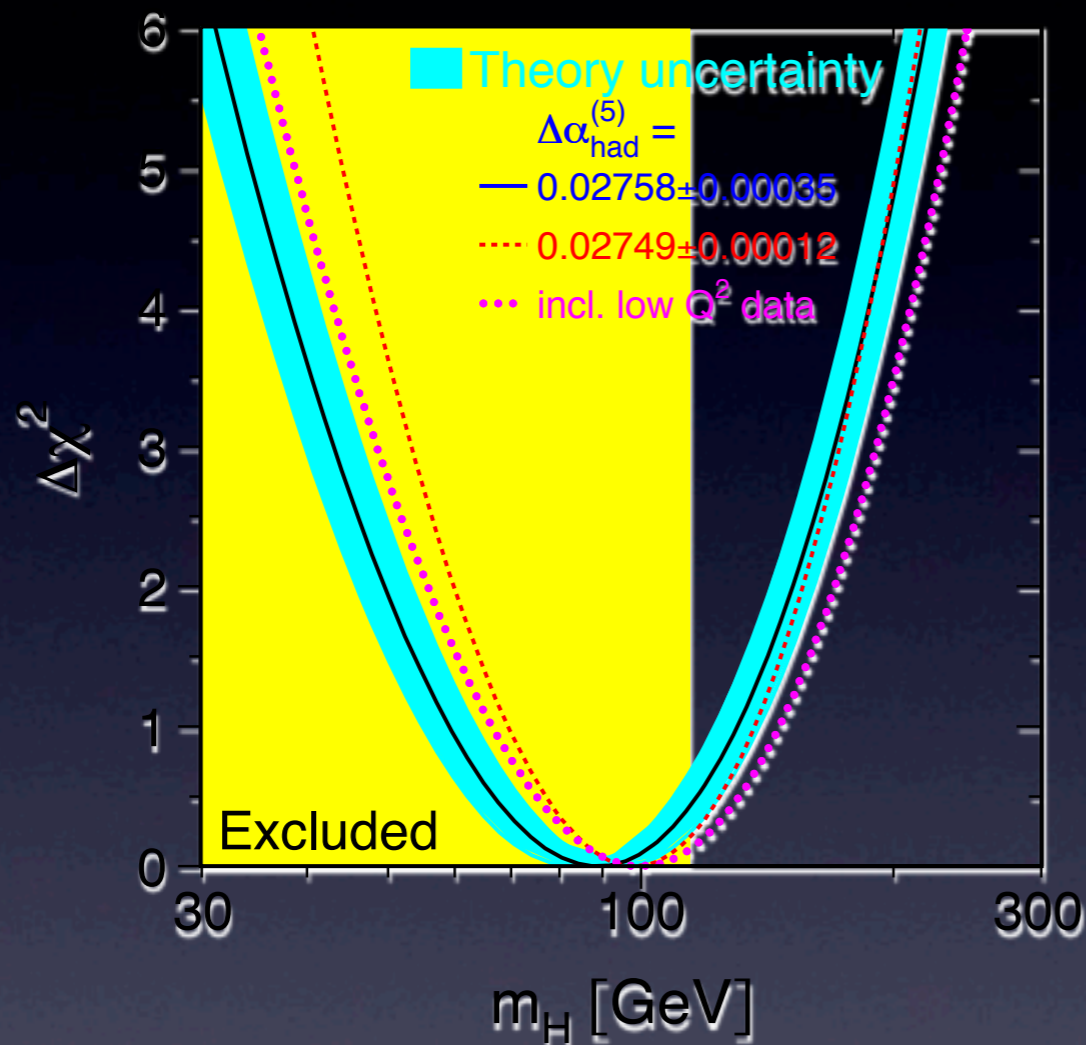
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So what does it tell us?

2006



$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

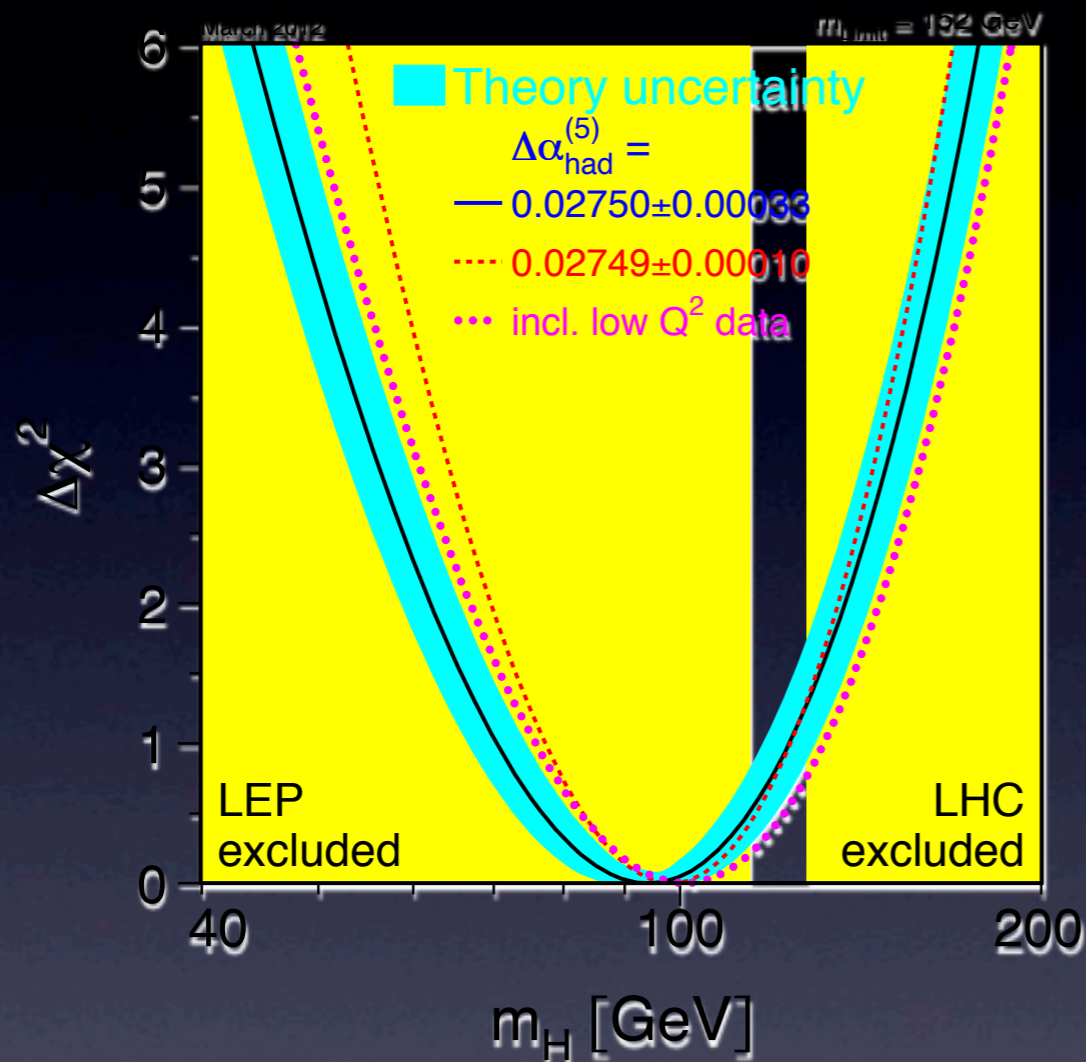


$$m_H < 152 \text{ GeV}$$

Direct searches:
 $m_H > 114 \text{ GeV}$

So what does it tell us?

2012



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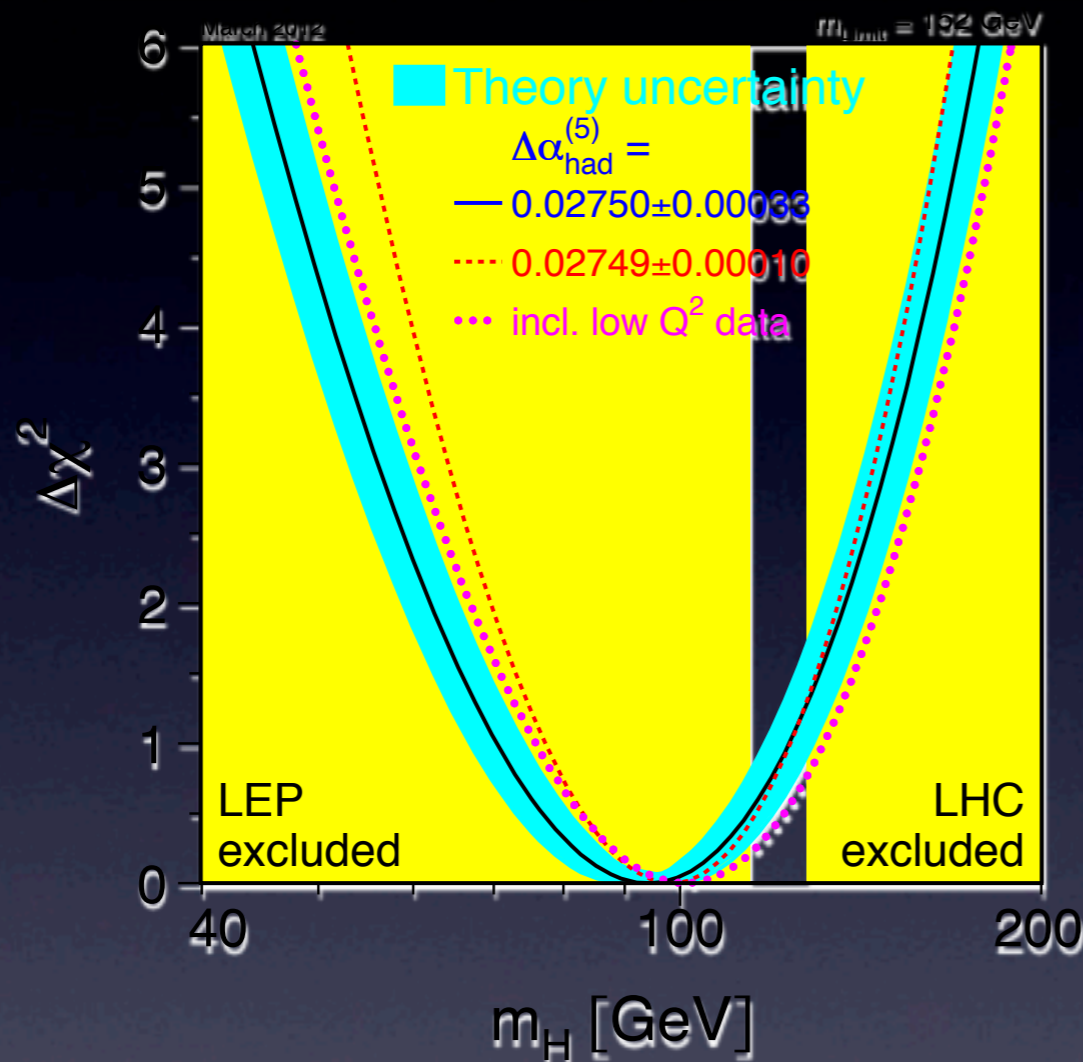


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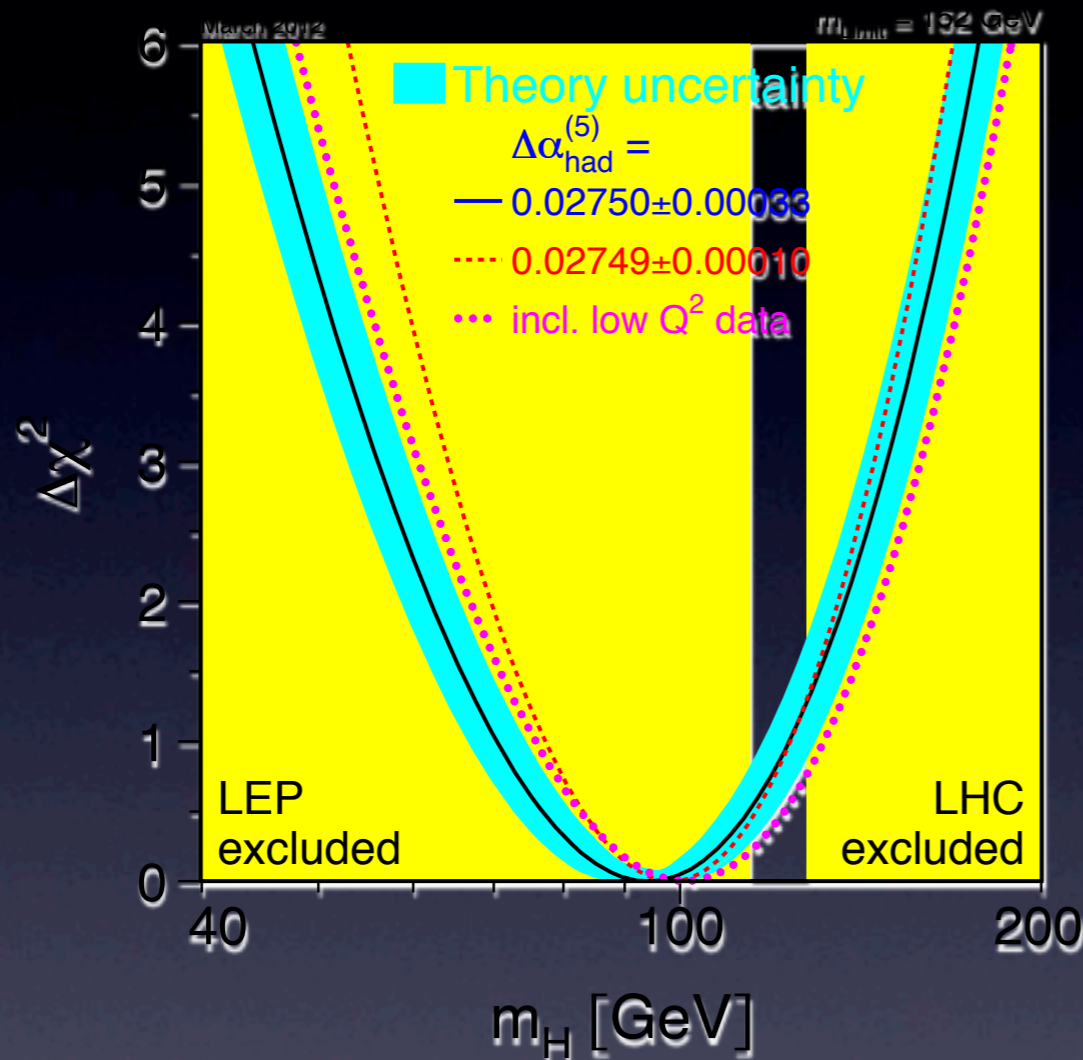
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So to look between 114 GeV and 152 GeV...

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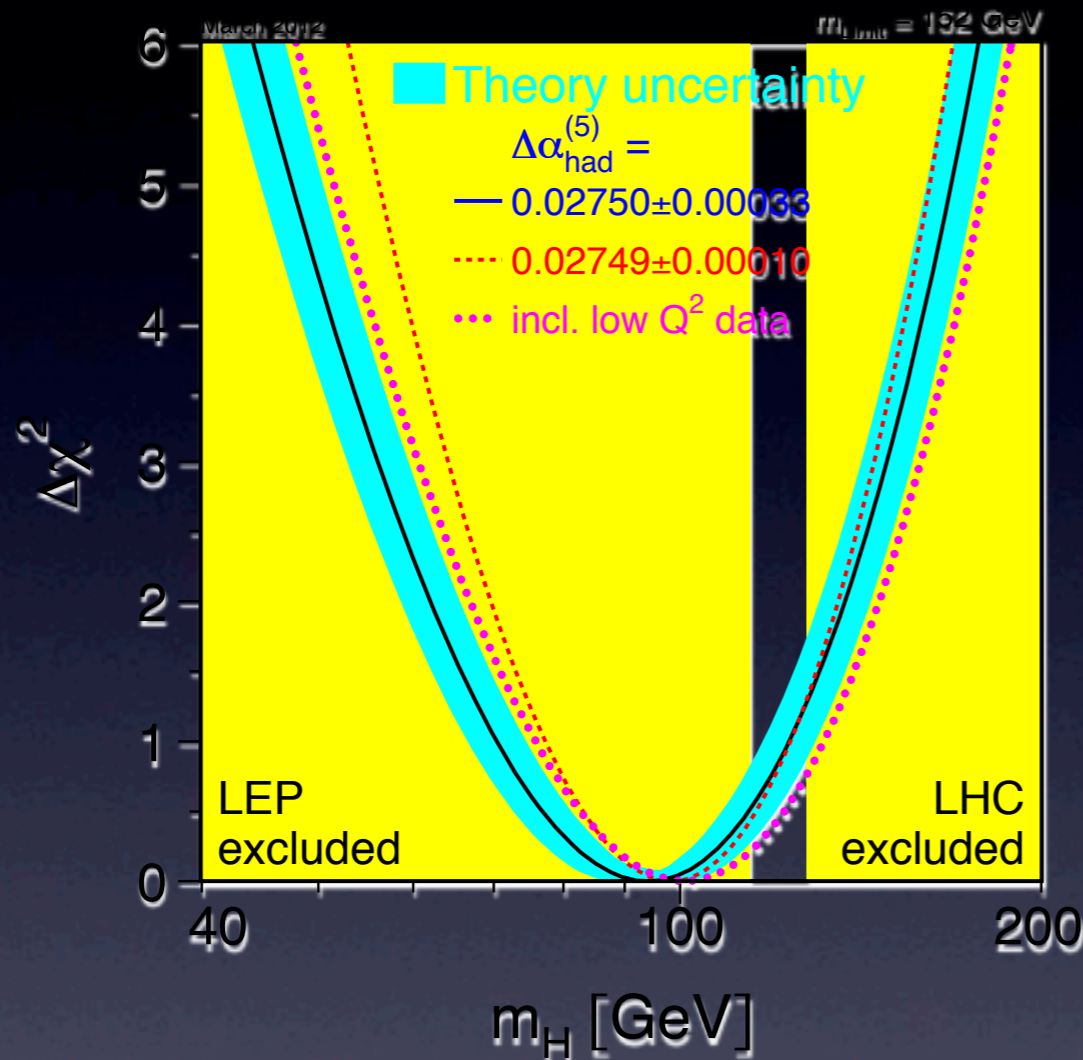
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So to look between 114 GeV and 152 GeV...

...we're going to need a bigger machine

So what does it tell us?

2012



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$$m_H < 152 \text{ GeV}$$

Direct searches:
 $m_H > 114 \text{ GeV}$

127

So to look between 114 GeV and 152 GeV...

...we're going to need a bigger machine

The Large Hadron Collider



- Proton-proton collider up to 7 TeV per beam (14 TeV collisions!)
 - Operated at 7 TeV in 2011, 8 TeV in 2012
- Two detector experiments: **ATLAS** and **CMS**
 - ~**3000** physicists each

The LHC by the numbers



Energy: 14 TeV = 7 x Tevatron

Length: 27 km = 4 x Tevatron

Magnetic Field: 8.3 T = 2 x Tevatron

Beam Energy: 350 MJ = 250 x Tevatron

Instantaneous Luminosity = 60 x Tevatron

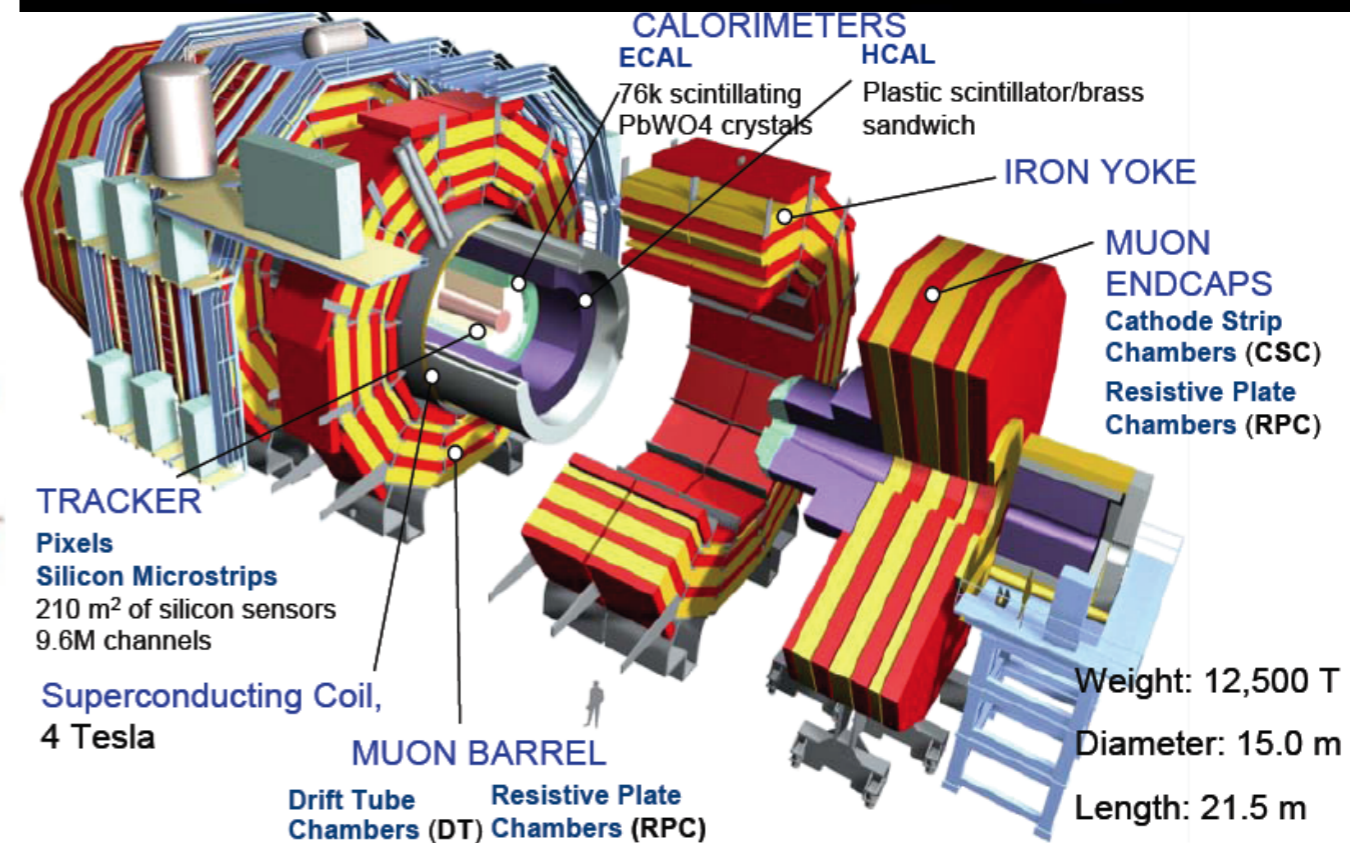
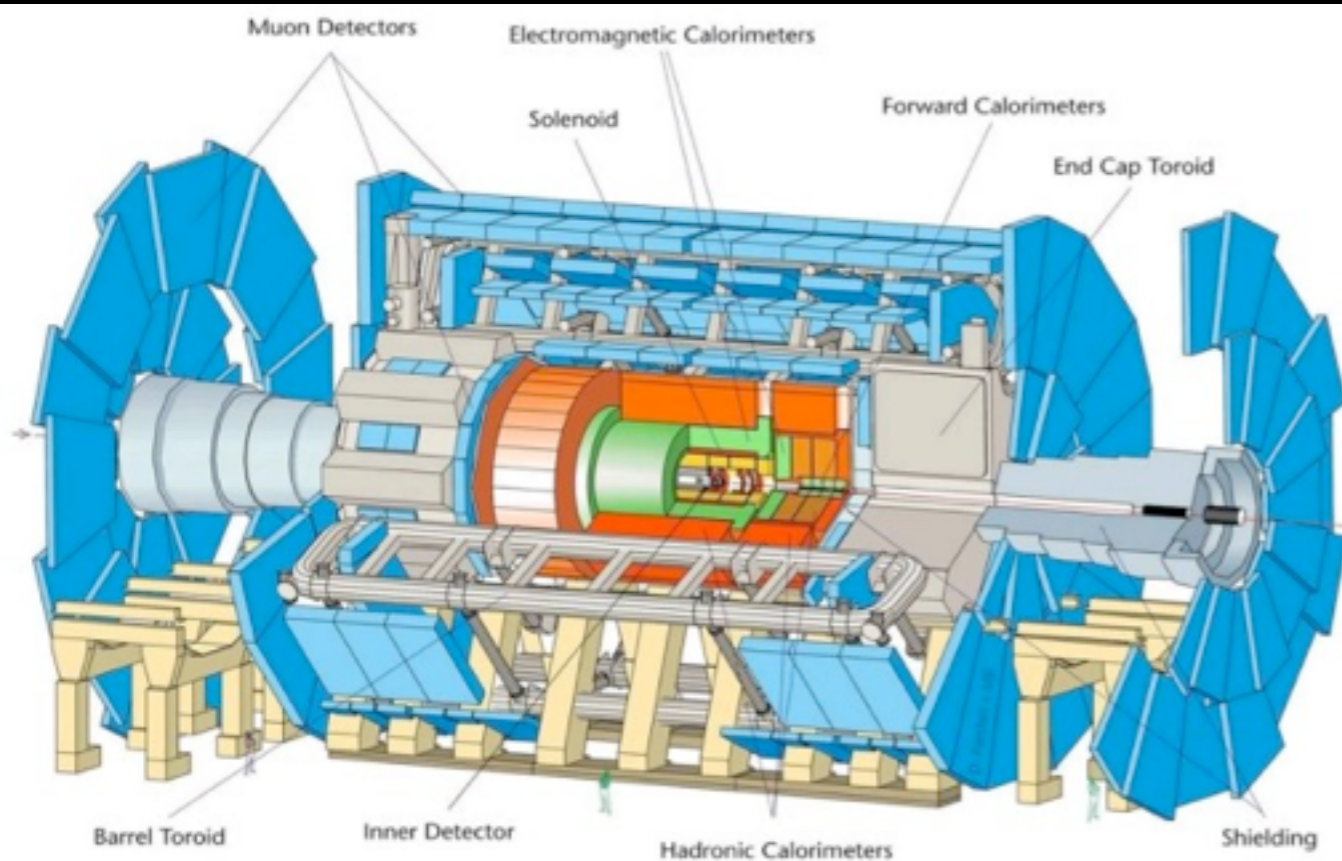
of Collisions in an event = 10 x Tevatron

Data Rate: 1 Terabyte / sec = 50 x Tevatron

of Detector Channels: 100 M = 100 x Tevatron

of Scientists (~3000/expt) = 4 x Tevatron

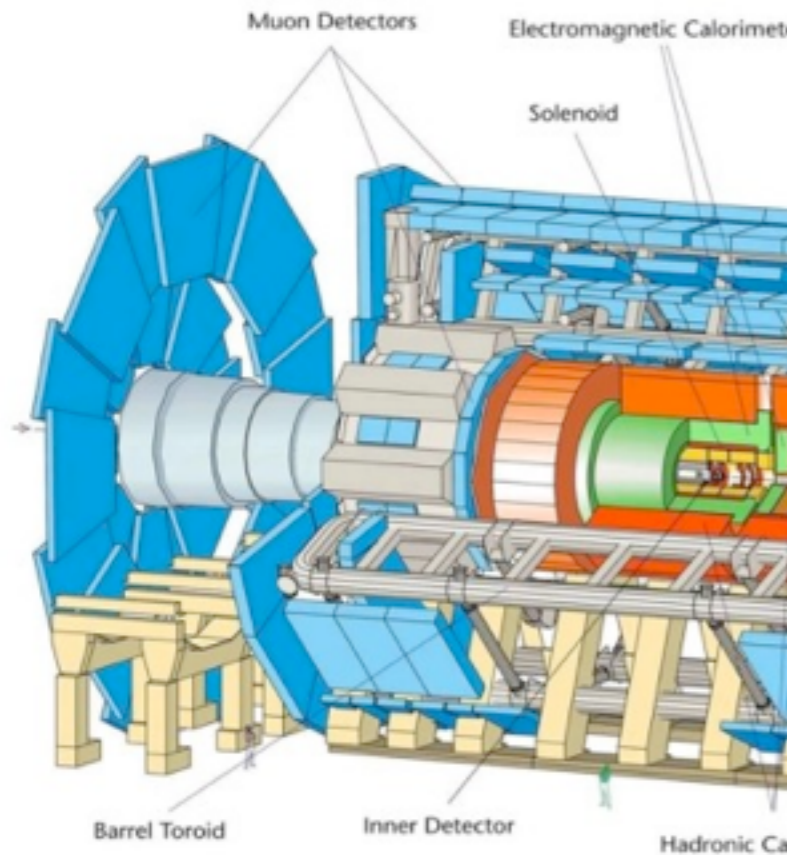
ATLAS and CMS



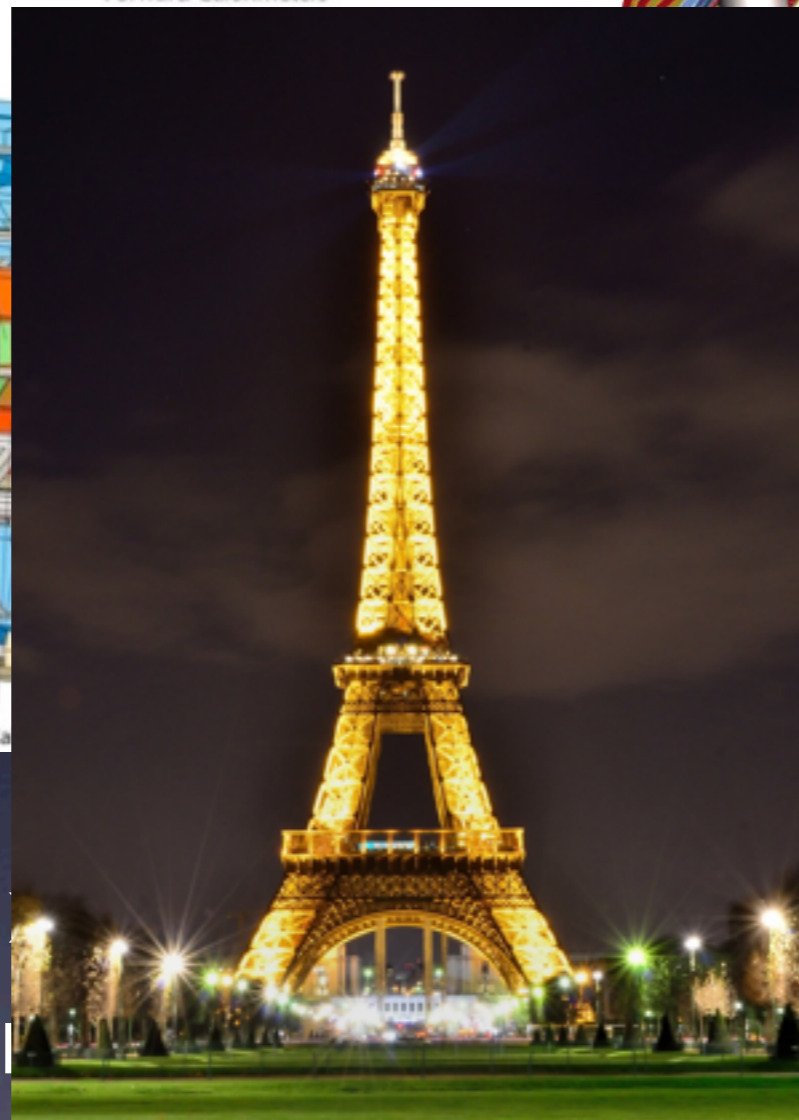
ATLAS: 42m x 22m
7,000 tons

CMS: 21m x 15m
12,500 tons

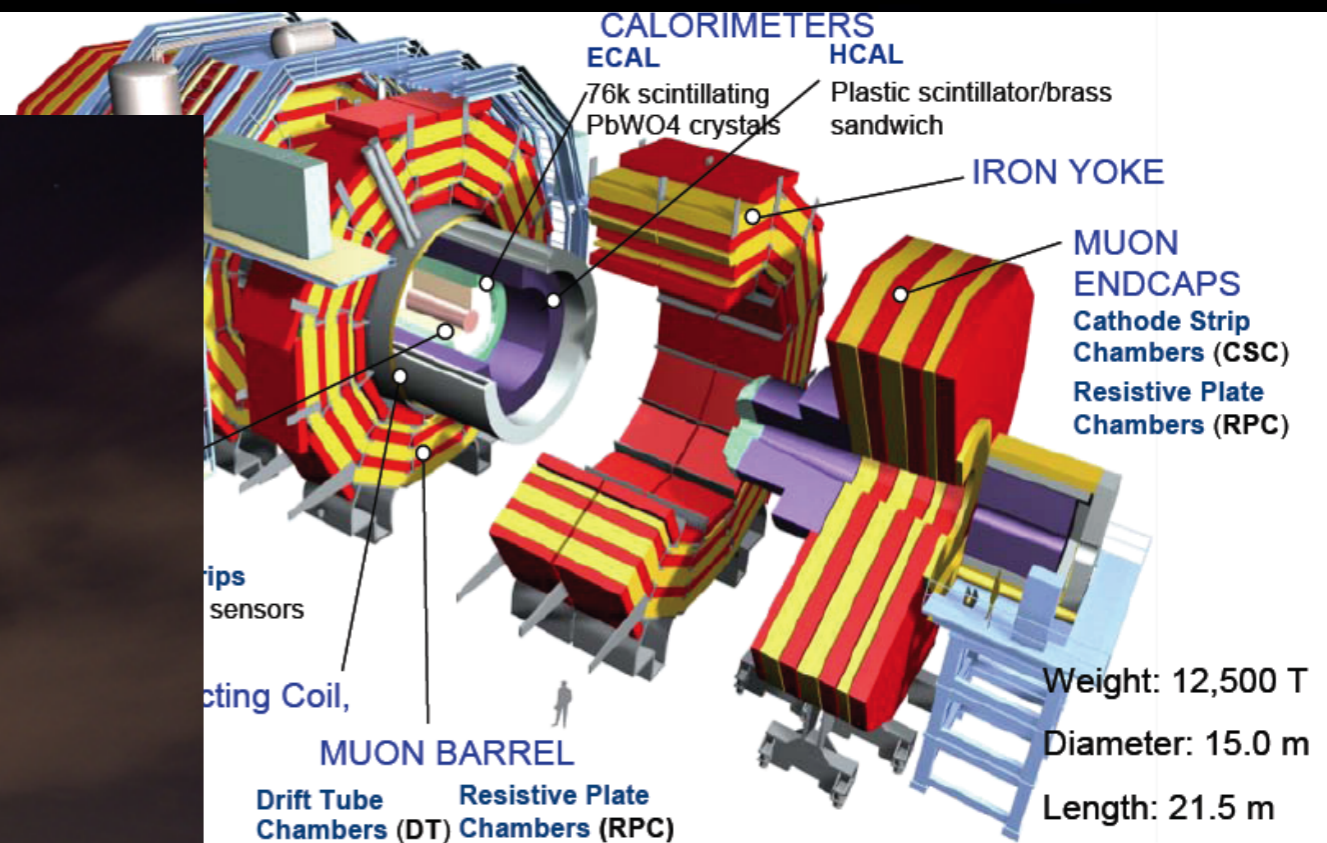
ATLAS and CMS



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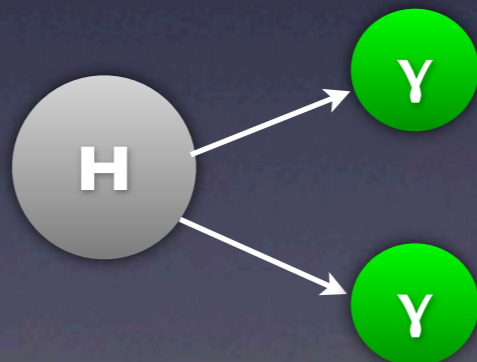
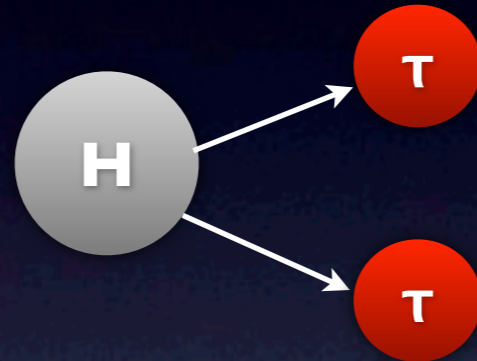
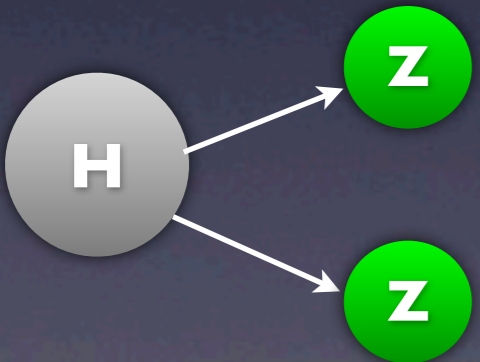
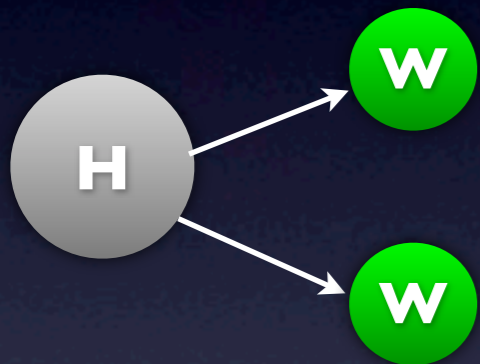
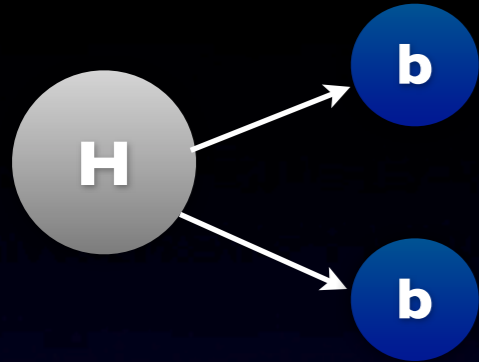


10,000 tons



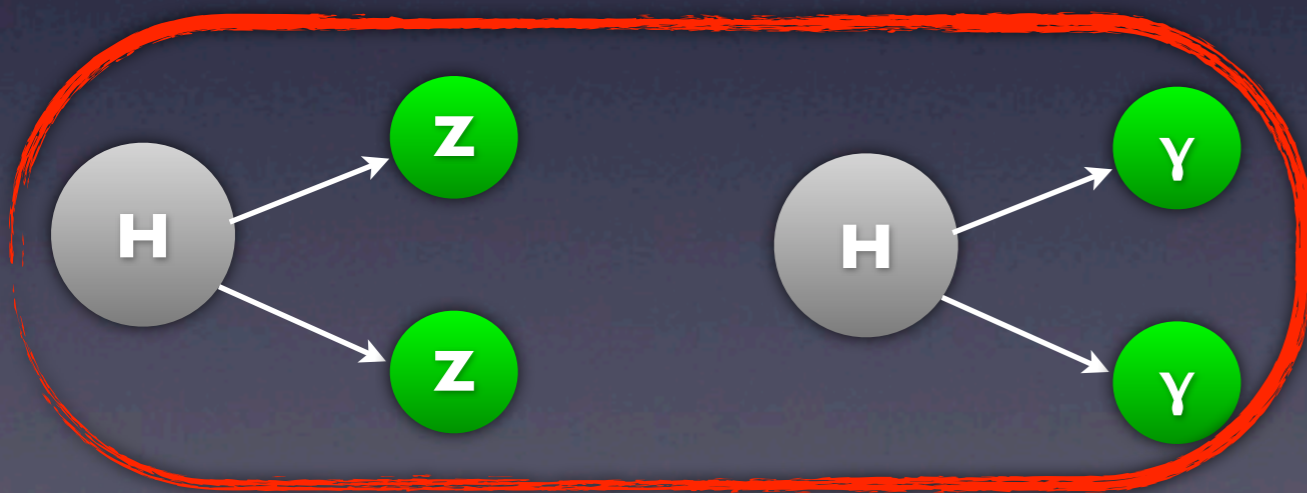
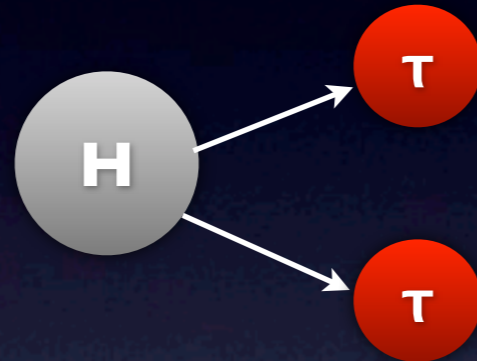
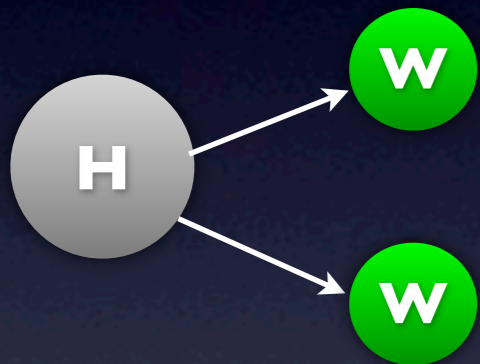
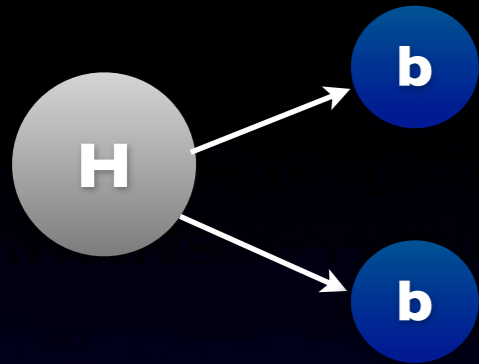
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Searching for the Higgs



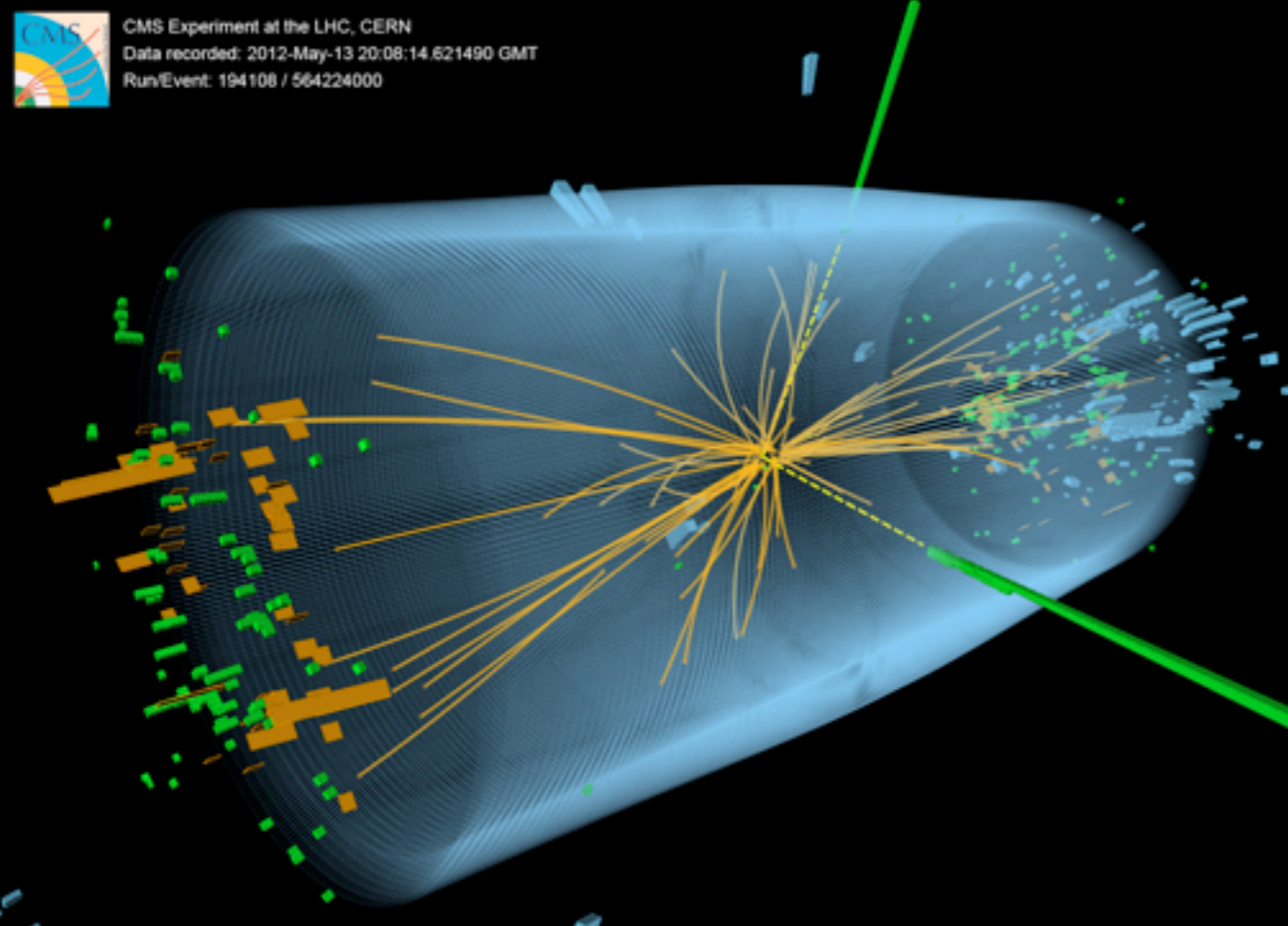
- Predicted Higgs production rate exceedingly rare
 - ~10000 times less frequent than W boson production
 - **1 in 10 billion collisions**
- Most common decay products also immediately decay
 - Nearly identical background processes are far more common

Searching for the Higgs



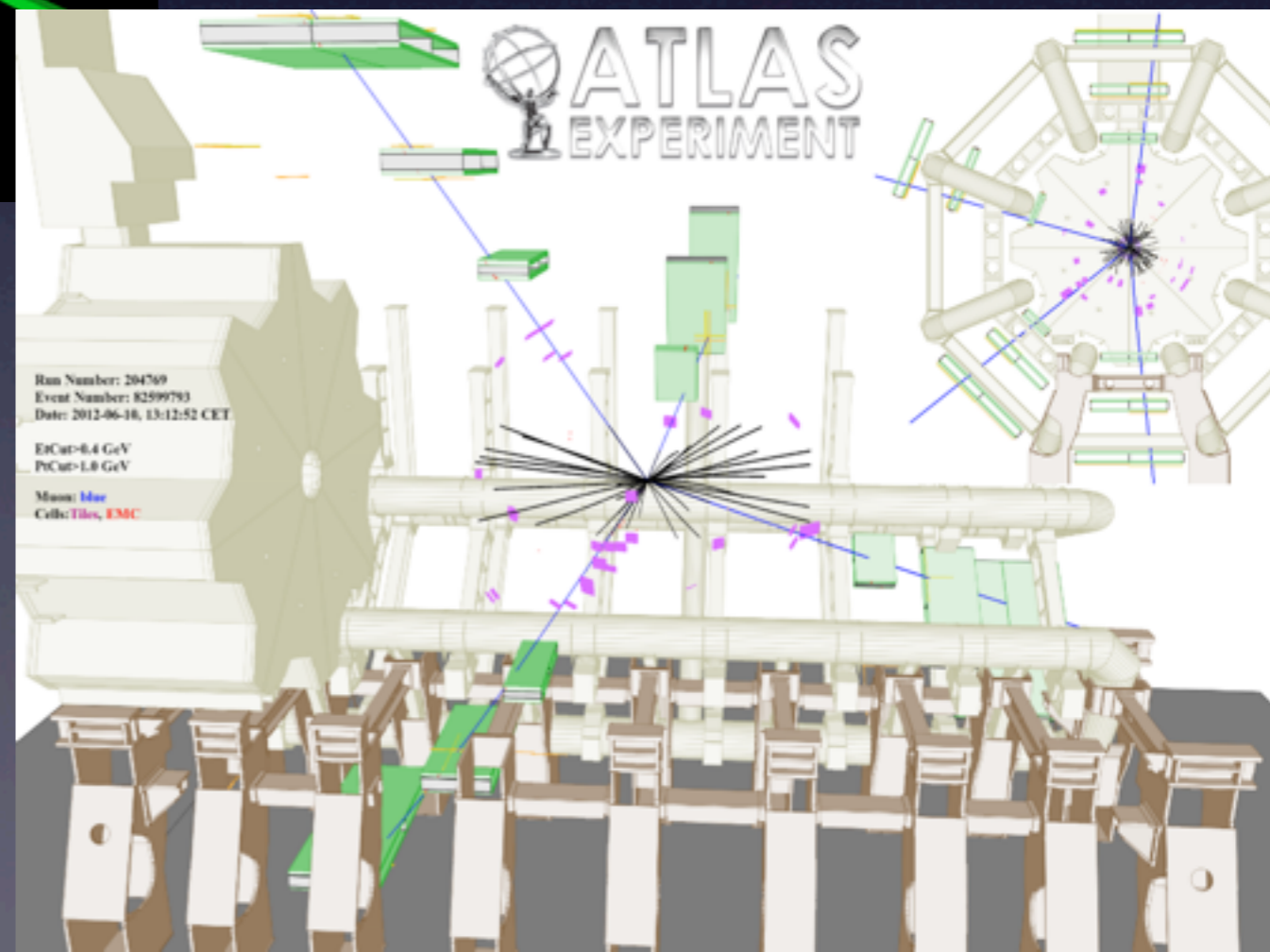
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Some candidate events

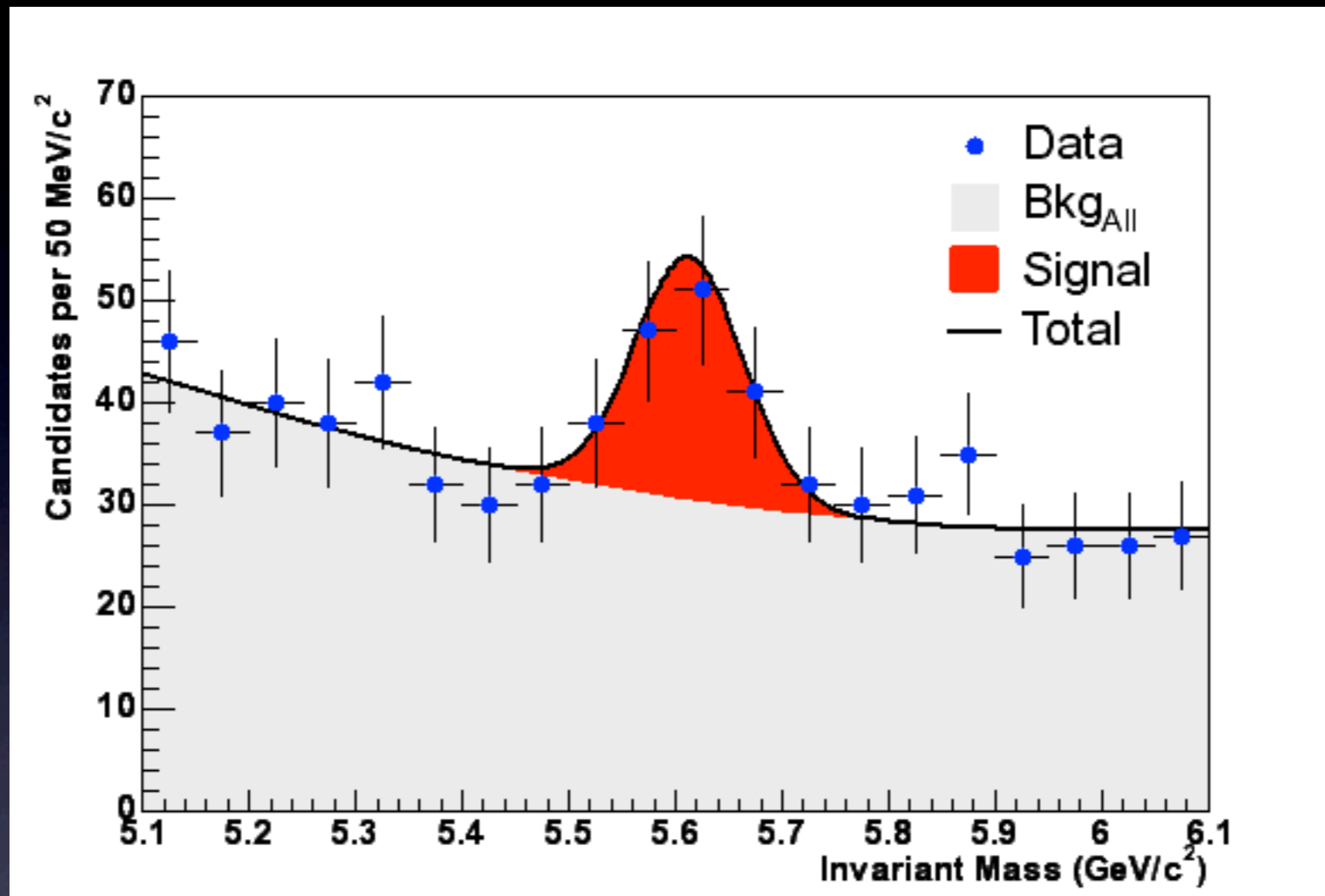


$H \rightarrow \gamma\gamma$ at CMS

$H \rightarrow ZZ$ at ATLAS

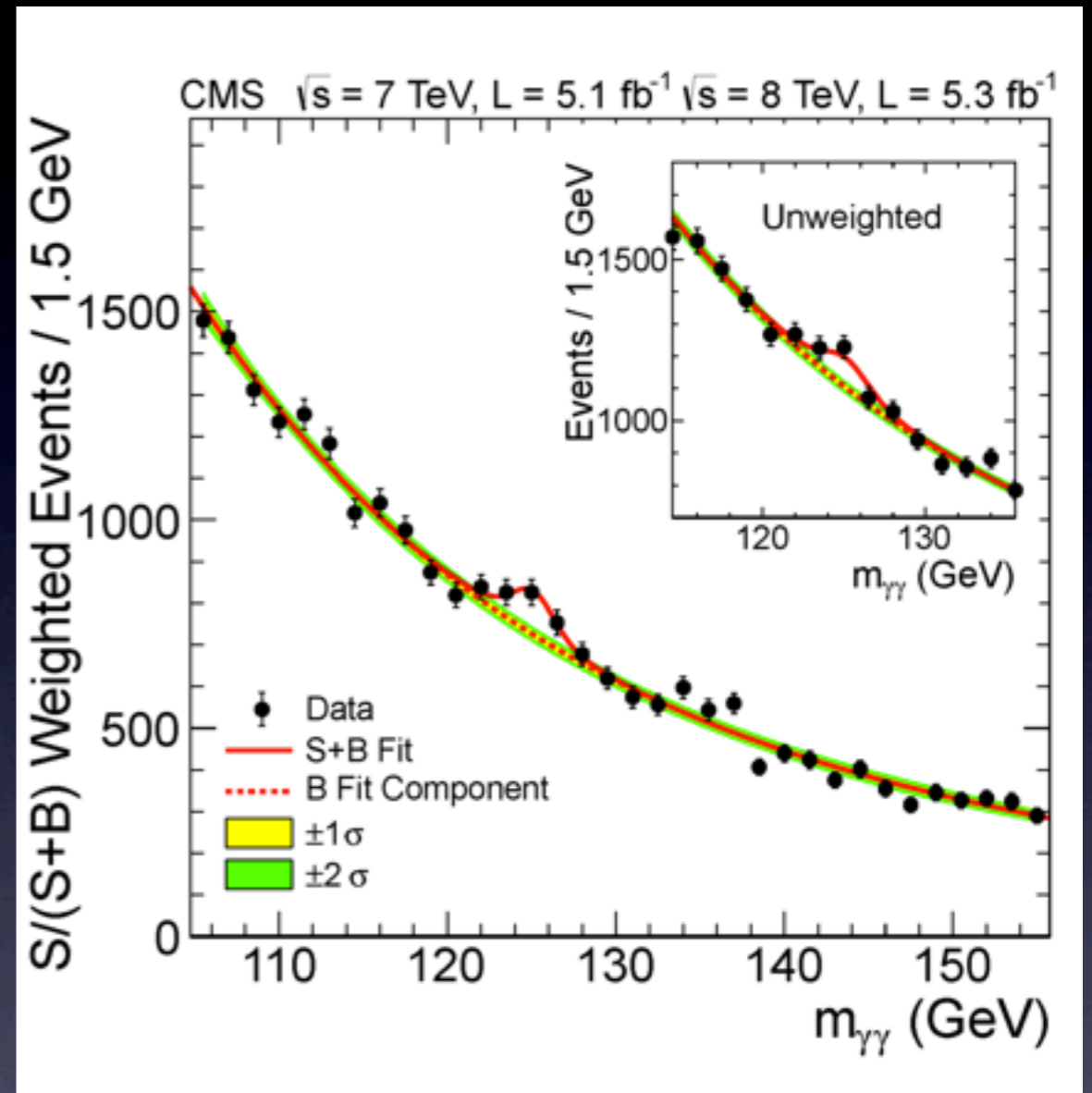
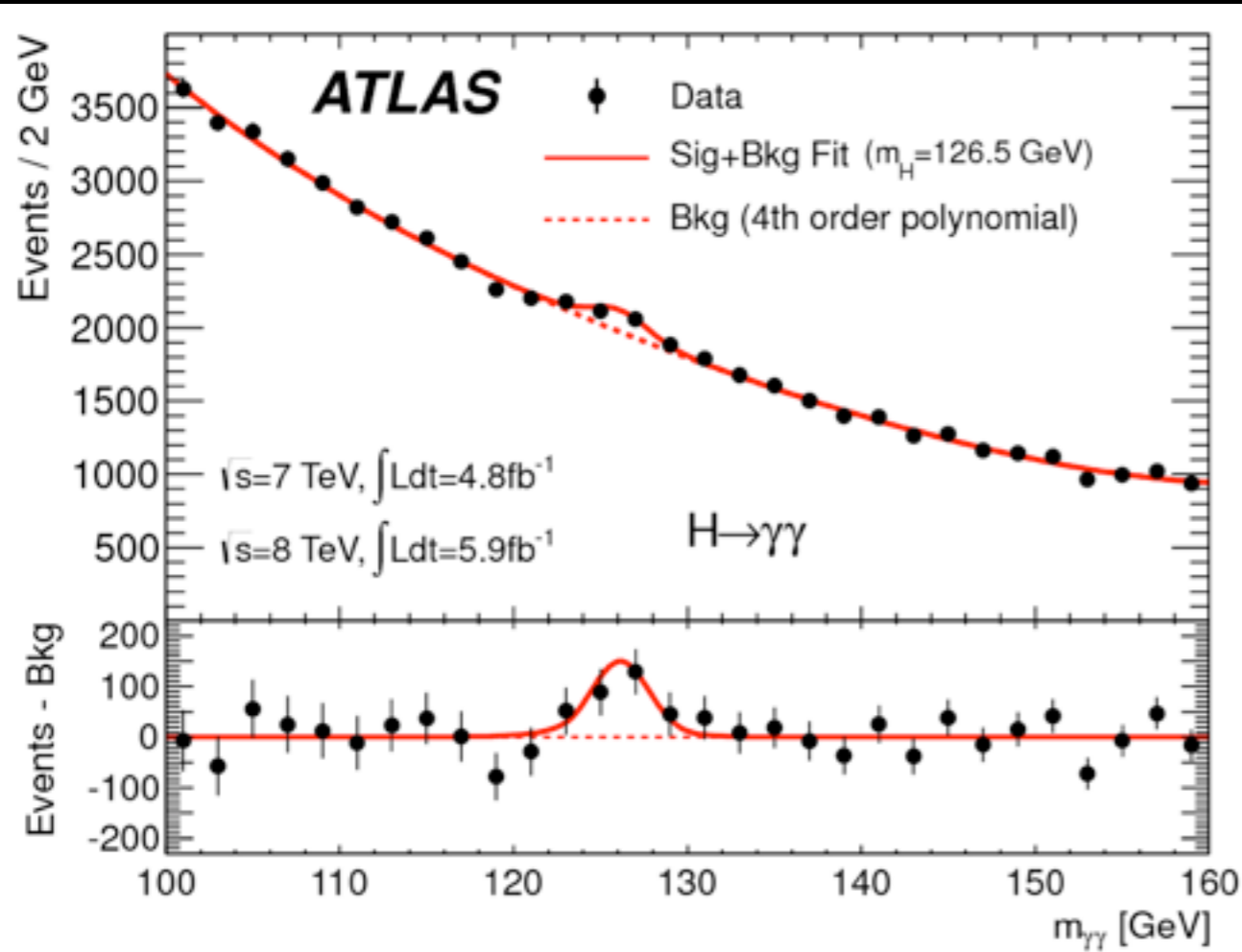


Bump Hunting

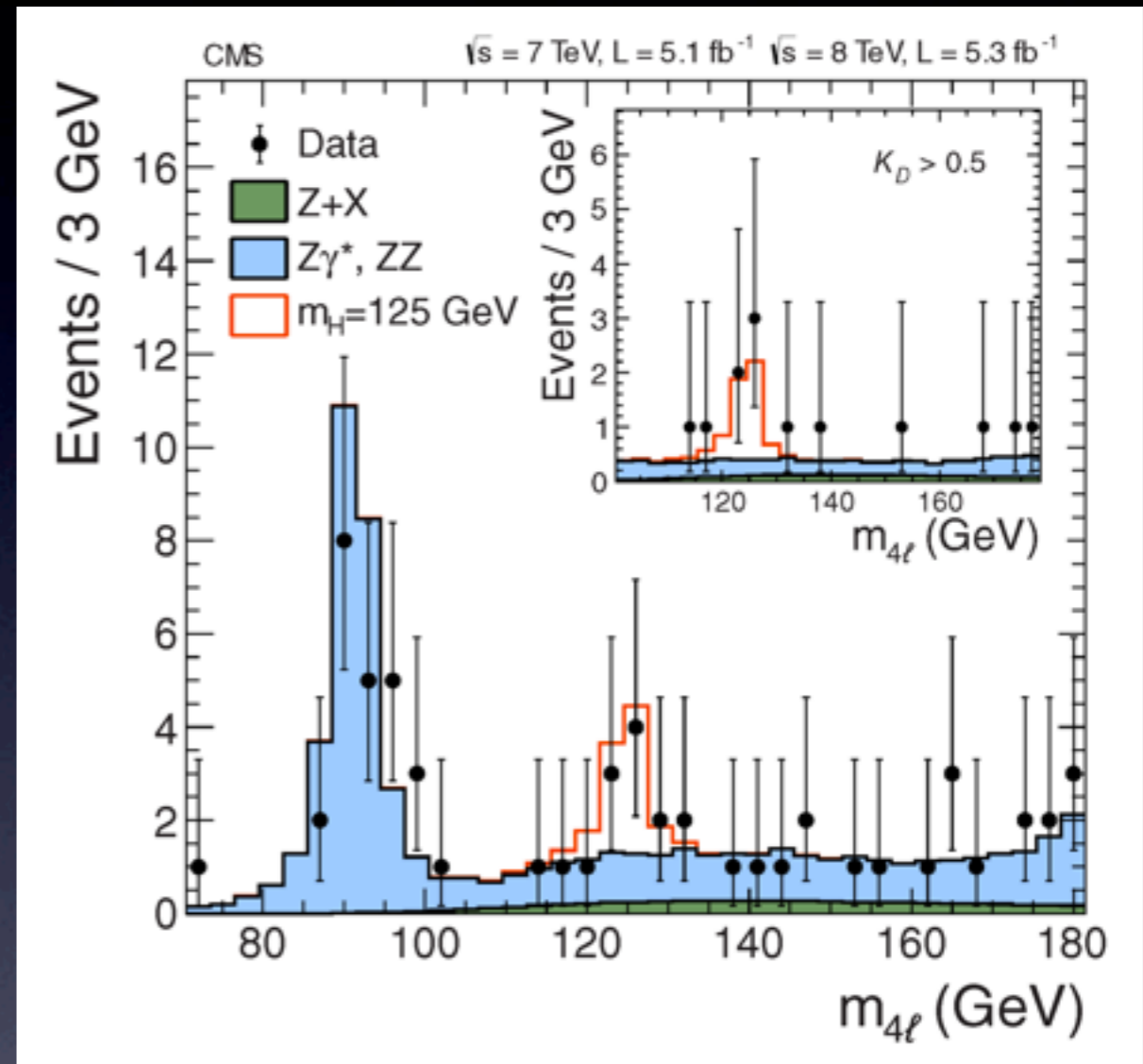
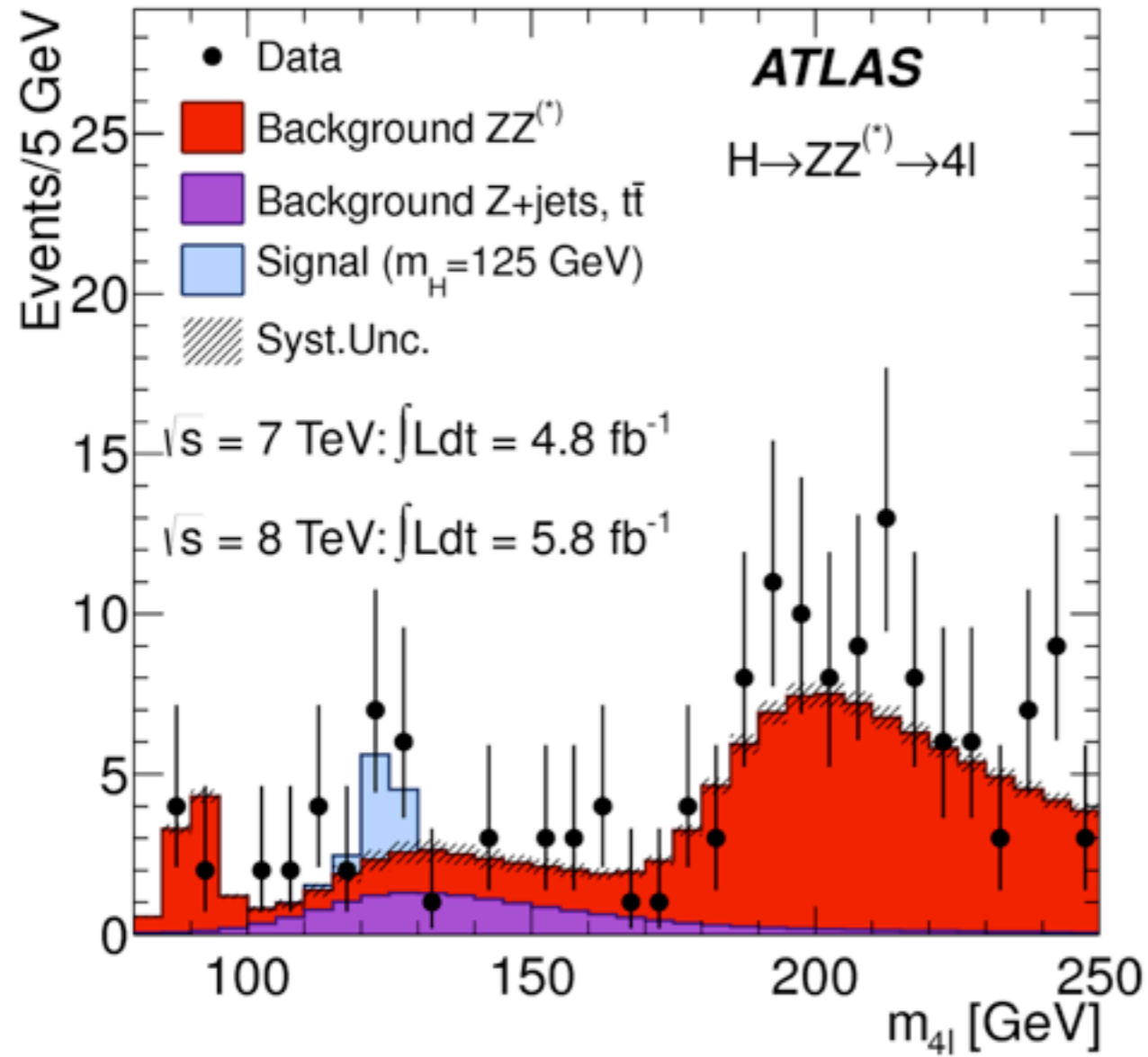


- Plot mass of data events (sum of decay energies)
- Look for peak over known backgrounds

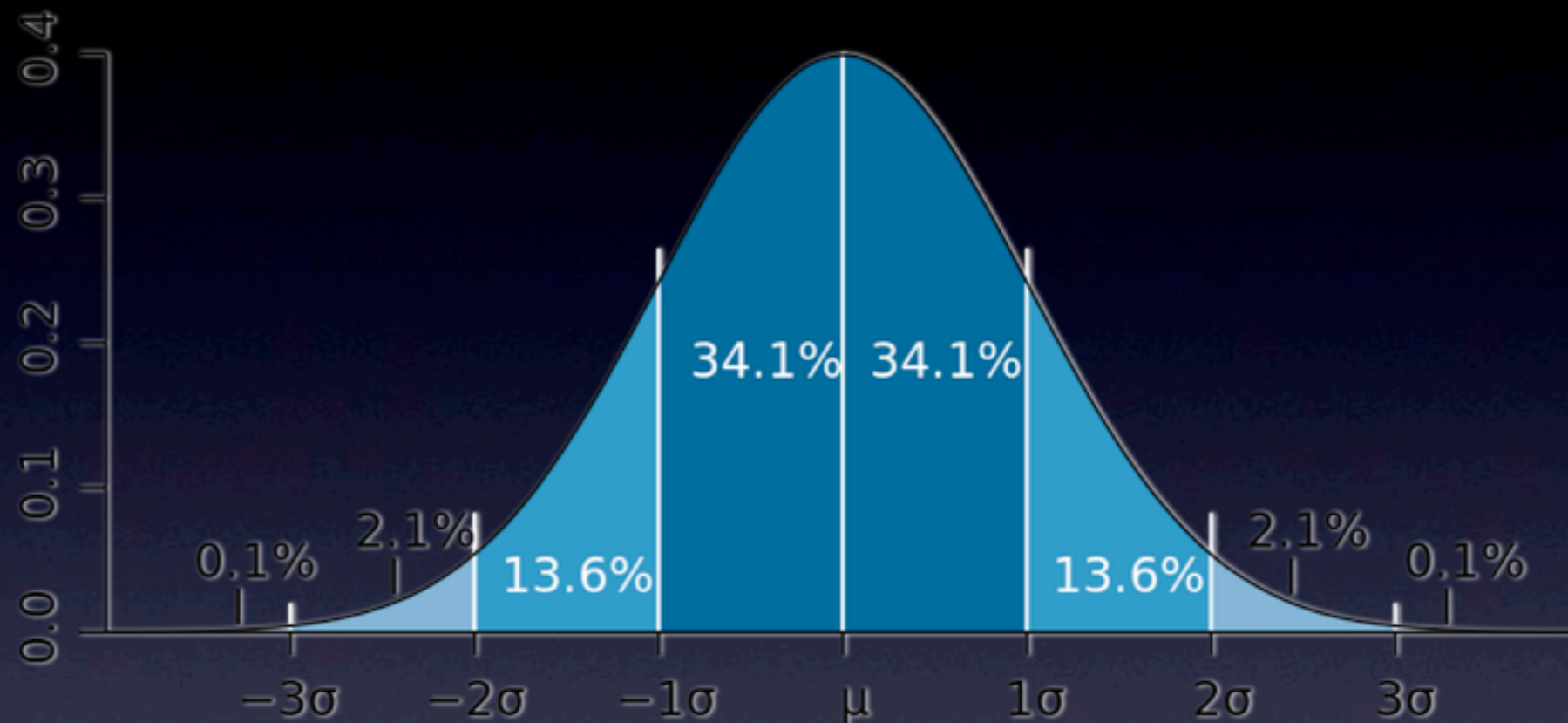
Higgs to Two Photons



Higgs to Two Z Bosons

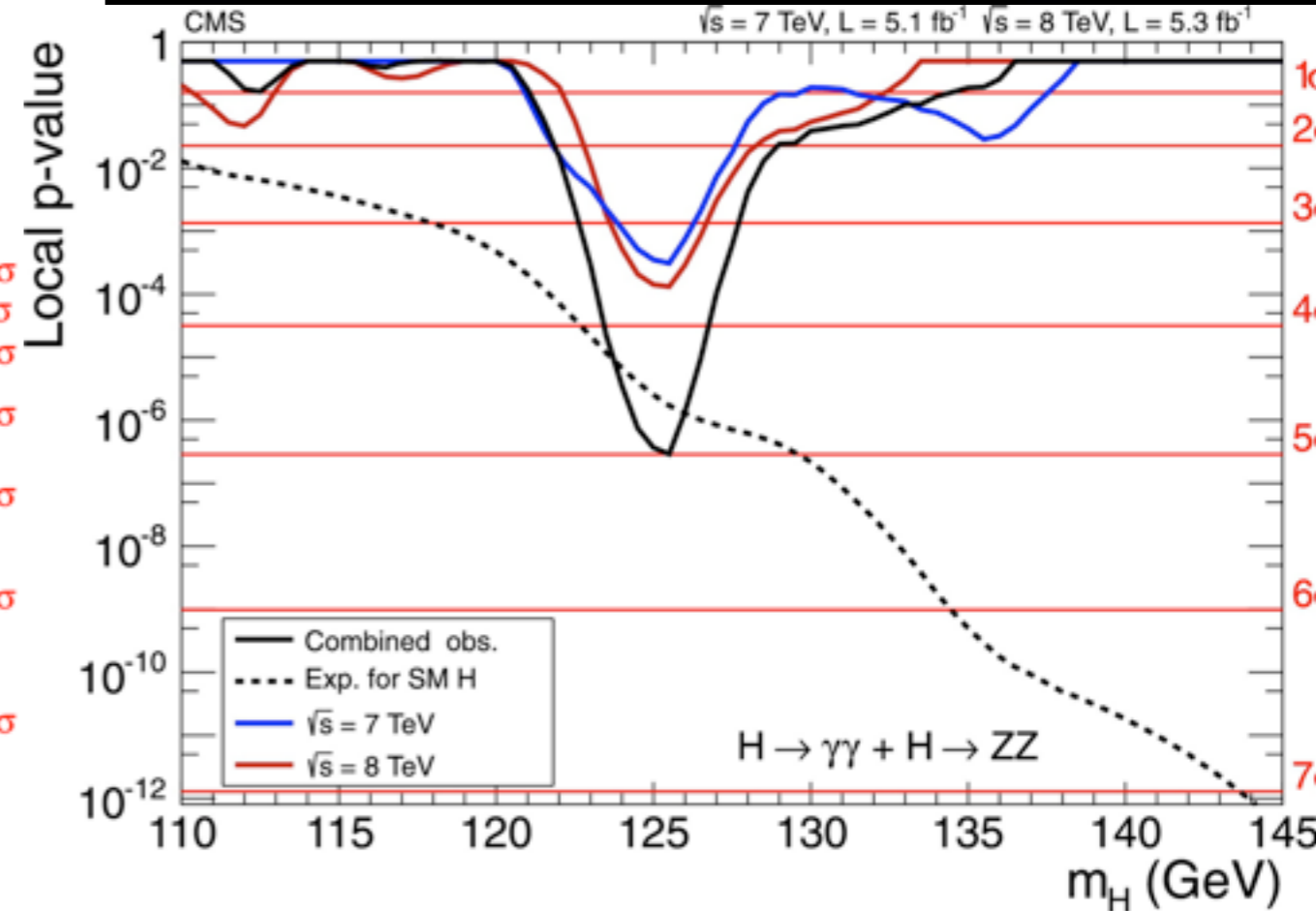
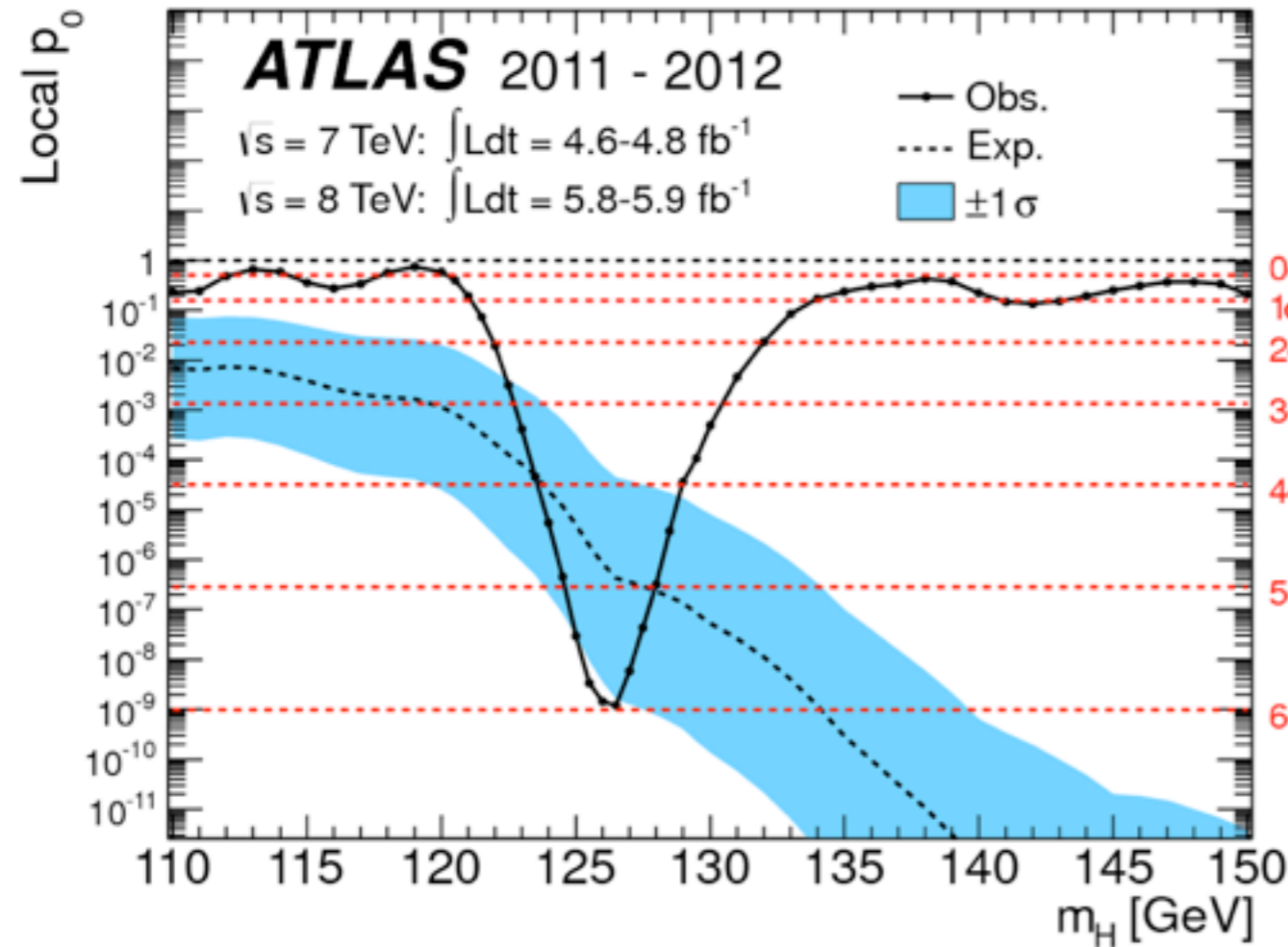


But how significant?



- A new particle is “discovered” only with 5σ significance
 - p-value of 3×10^{-7}
 - Observed data must be no more likely than **1-in-3.5 million** to have been produced in the absence of the new particle

July 4, 2012



5 σ significance at both experiments!

A new particle with mass 125 GeV is discovered

DIGITAL SUBSCRIPTION: 4 W

Search



Pool photo by Denis

New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva, could explain the universe's origin.

INTERNATIONAL

CNNI CNN en Español

Notification preference

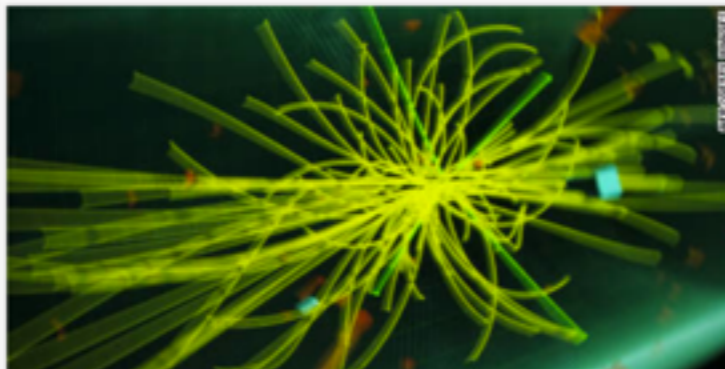
Video World U.S. Africa Asia Europe Latin America Middle East Business World S

2012 — Updated 1047 GMT (1847 HKT)



clear scientists reveal Higgs discovery

Scientists say they are almost certain they have discovered the Higgs boson particle — which could help unlock some of the universe's best secrets. [FULL STORY](#)



Why 'God Particle' is key to universe

Scientists have moved closer to proving the existence of the Higgs boson — the so-called 'God Particle' — thought to be a fundamental building block of the universe. But exactly what is it? CNN explains. [FULL STORY](#)

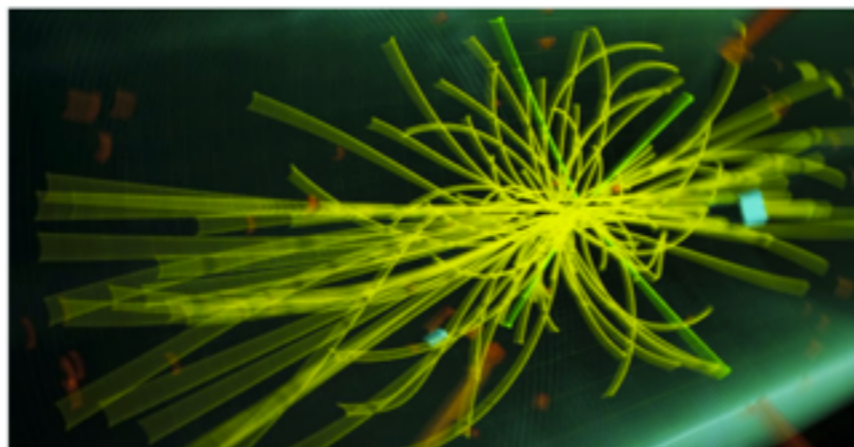
Mise à jour à 10h02 — Paris

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EN CE MOMENT Nicolas Sarkozy Mali Boson de Higgs 1962 : l'indépendance algérienne

Le boson de Higgs découvert avec 99,9999 % de certitude



Voici la confirmation tant attendue : une nouvelle particule a été découverte au Centre européen de recherche nucléaire (CERN), près de Genève.

Boson de Higgs : la fin de la traque

Le boson de Higgs : les raisons d'une quête



[Back to previous page](#)

Scientists' search for Higgs boson yields new subatomic particle

By [Brian Vastag](#) and [Joel Achenbach](#), Published: July 4, 2012

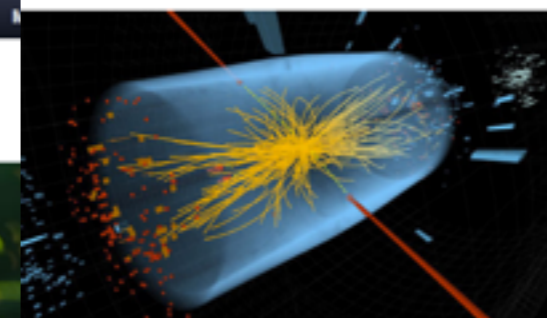
INTERNACIONAL POLÍTICA ECONOMÍA CULTURA SOCIEDAD

ESTÁ PASANDO Bosón Higgs Amnistía fiscal Código Calabino Incendios Valencia Caso Barclays Caso Bettencourt Vols

DIRECTO Los científicos del CERN anuncian el descubrimiento de una partícula que podría ser Higgs. Sigue la videoconferencia explicando un avance que, de confirmarse, supondría un paso esencial de la física para explicar el origen de la materia. »

Hallada "la más sólida evidencia" de la existencia del bosón de Higgs

El posible descubrimiento de la partícula es un paso esencial hacia la explicación del origen de la materia



registro del CMS que pudiera ser la firma de la partícula de Higgs. / CERN

"Puedo confirmar que se ha descubierto una partícula que es consistente con la teoría del bosón de Higgs", dicen los científicos. El descubrimiento de la partícula ayudaría a explicar el origen de la masa. Los físicos del CERN explican en estos momentos sus hallazgos

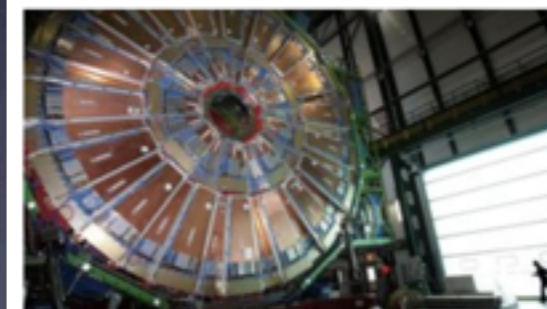
- [Diccionario para entender en qué consiste el hallazgo](#)
- [La "caza" del bosón de Higgs, por A. RUIZ JIMENO](#)
- [VIDEO Una explicación del bosón de Higgs](#)
- [Sigue en directo la conferencia del CERN](#)
- [FOTOGALERÍA Indicios hallados de la 'partícula de Dios'](#)
- ['Hacia la partícula de Dios', por JAVIER SAMPEDRO](#)

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4 July 2012 Last updated at 07:56 ET

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Scientists claim new particle discovery



Scientists in Europe claim they have discovered a new particle consistent with the long-sought Higgs boson. [671](#)

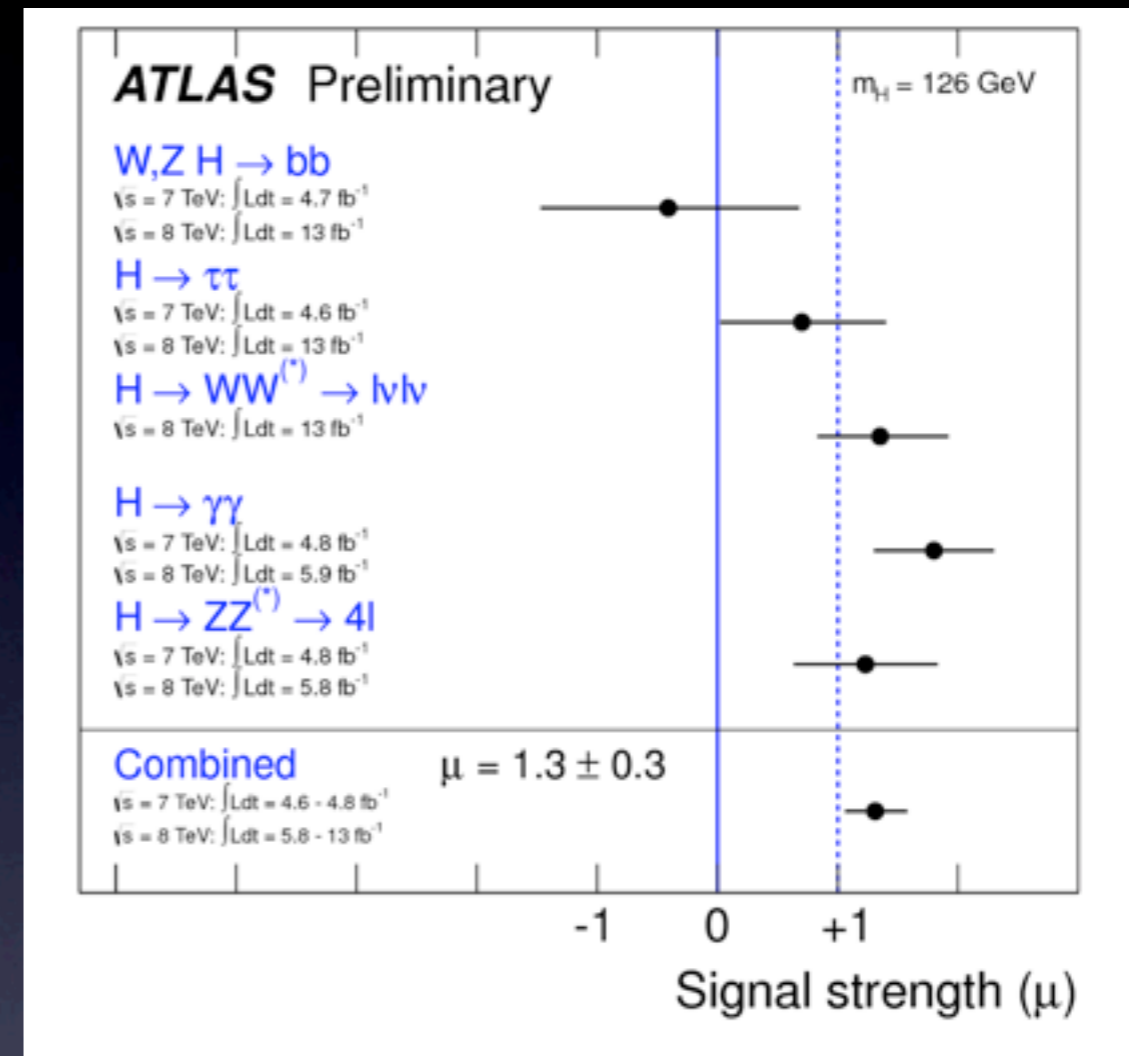
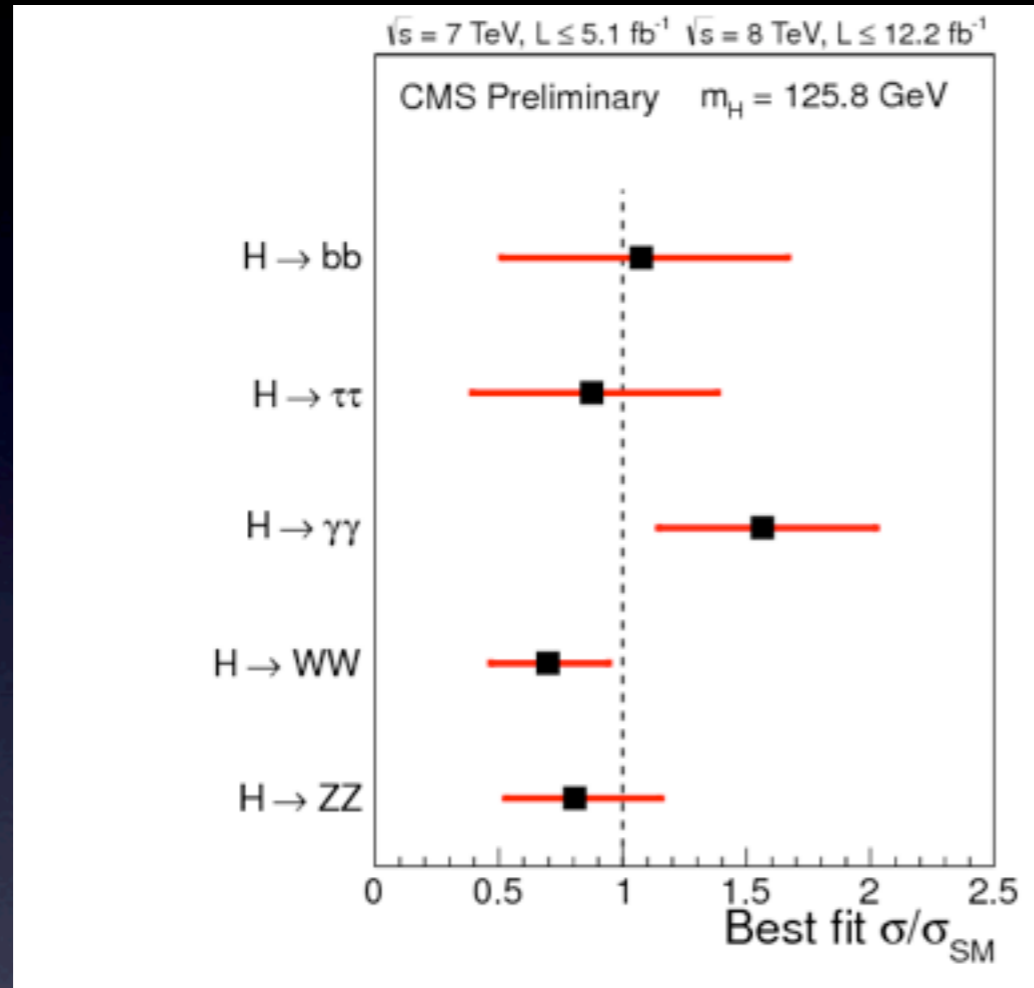
Q&A: The Higgs boson

► [Higgs boson: 'We have it'](#)

► [What is the Higgs?](#)

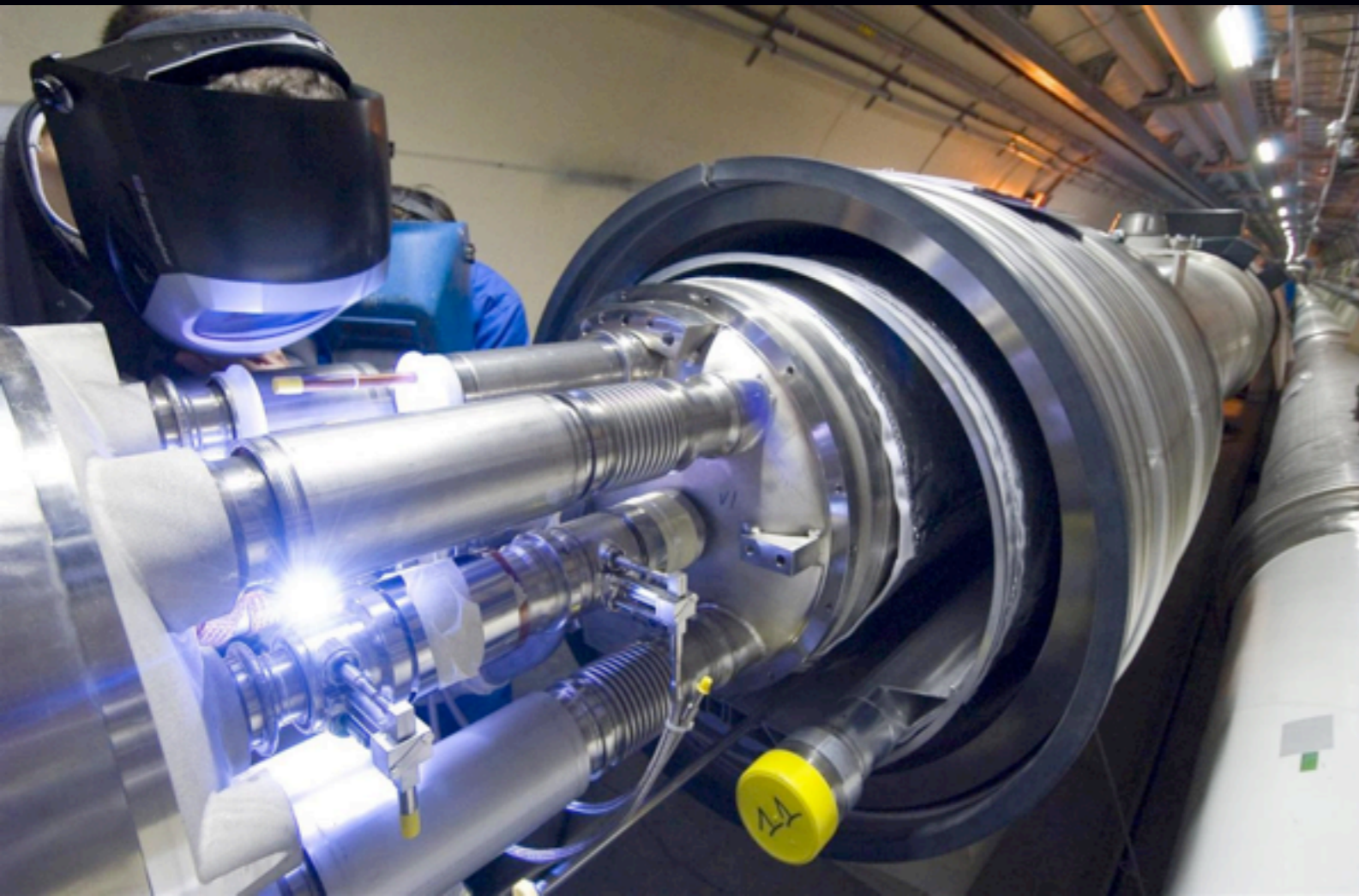
US sees stronger hints of Higgs

Well, what is it?



- Answer: a “Higgs-like boson”
- Definitely a new particle, but...
- Not all predicted decays seen with ample significance
 - Need more data!

What's next?



- LHC shut down for ~ 2 years (last week!)
 - Magnet upgrades to achieve design energy (14 TeV)
- Additional data in 2015 and beyond can (hopefully!) close the loop on the Higgs boson

Conclusion: just the beginning

- Many unanswered questions:
 1. Why do particles have mass?
 2. What is “dark matter”?
 3. How does gravity work?
 4. What happened to all the antimatter?
 5. What is “dark energy”?

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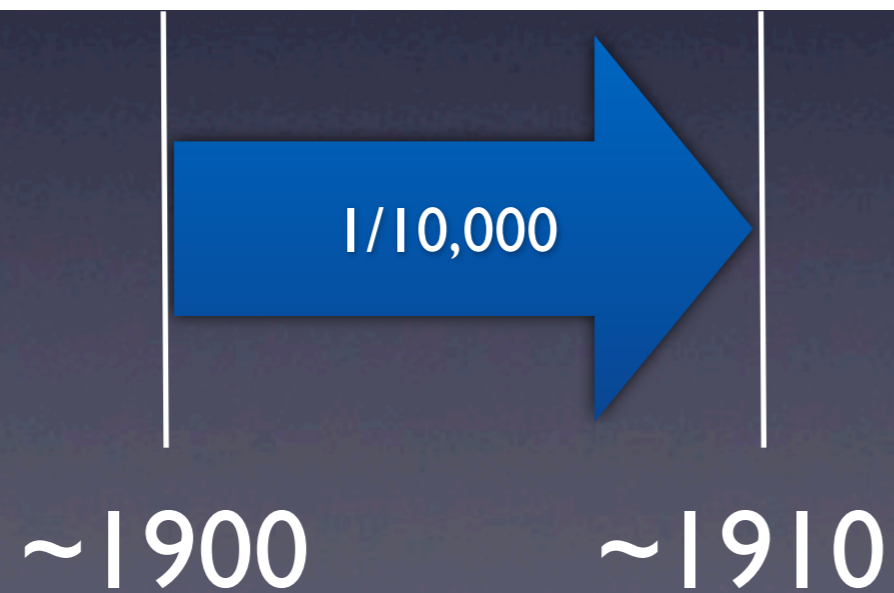
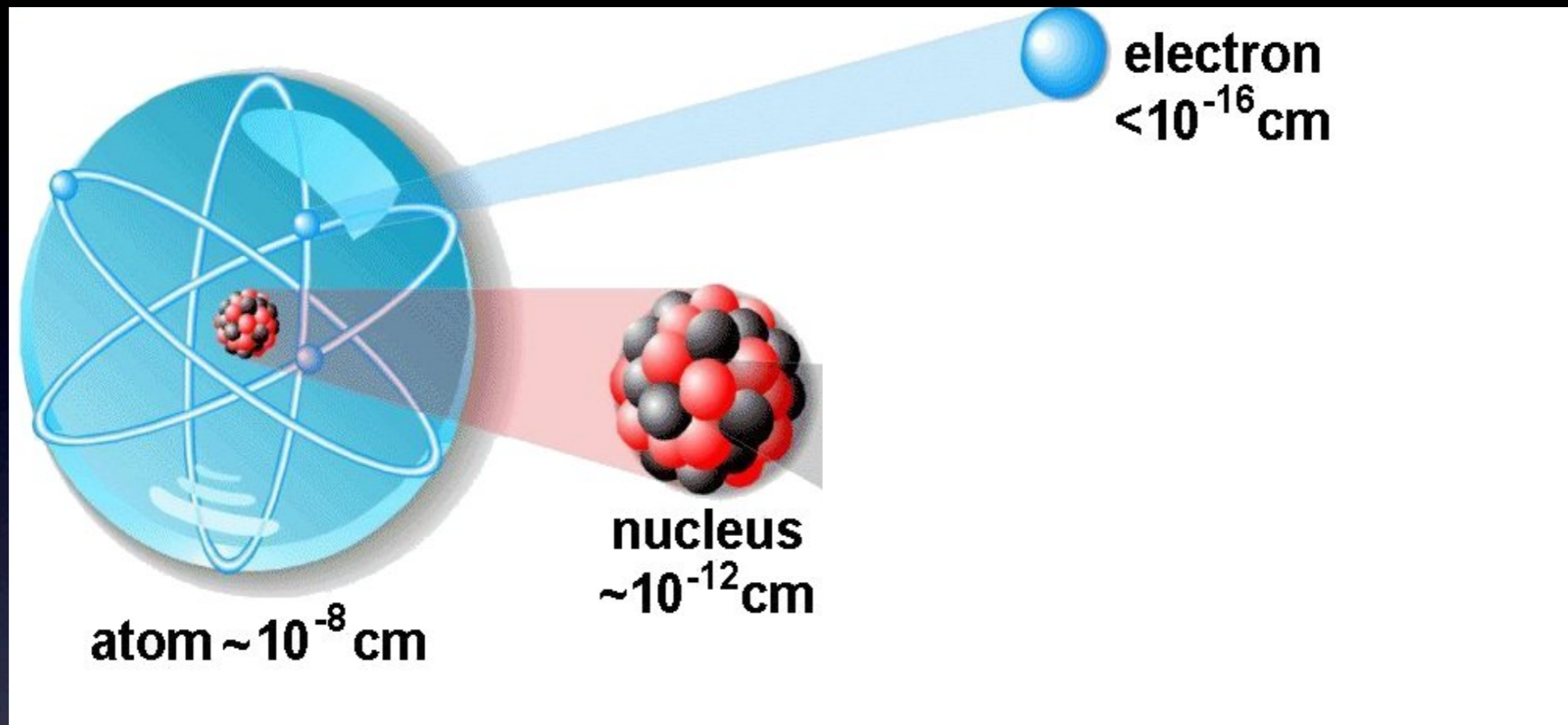
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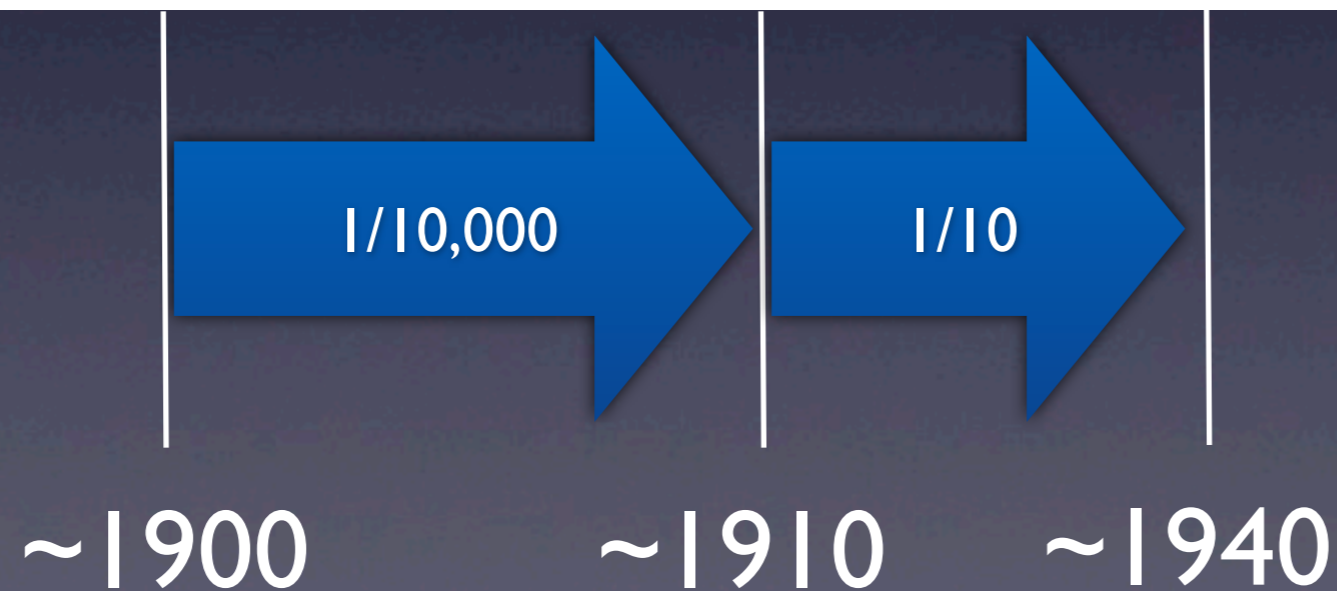
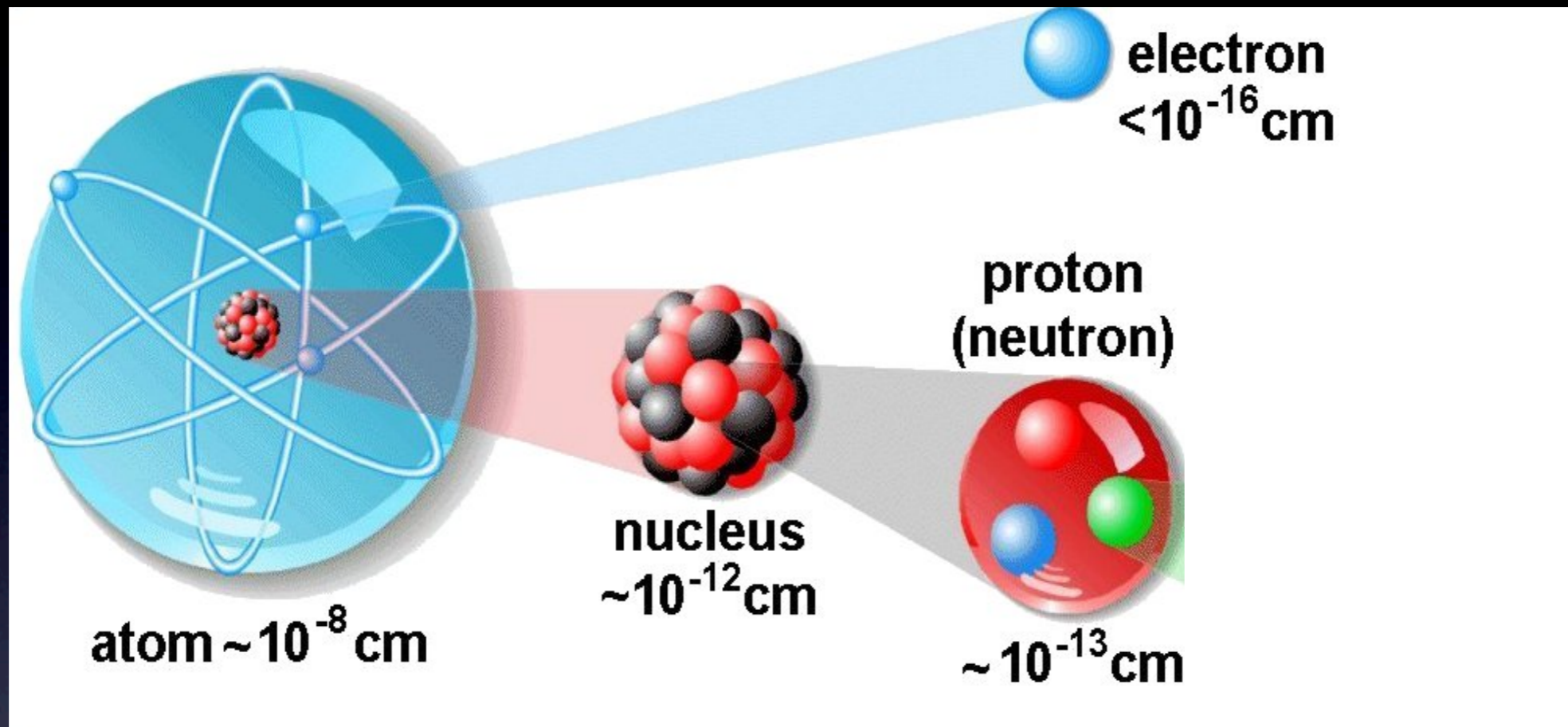
The LHC could provide insight to all of these
Stay tuned

Backup

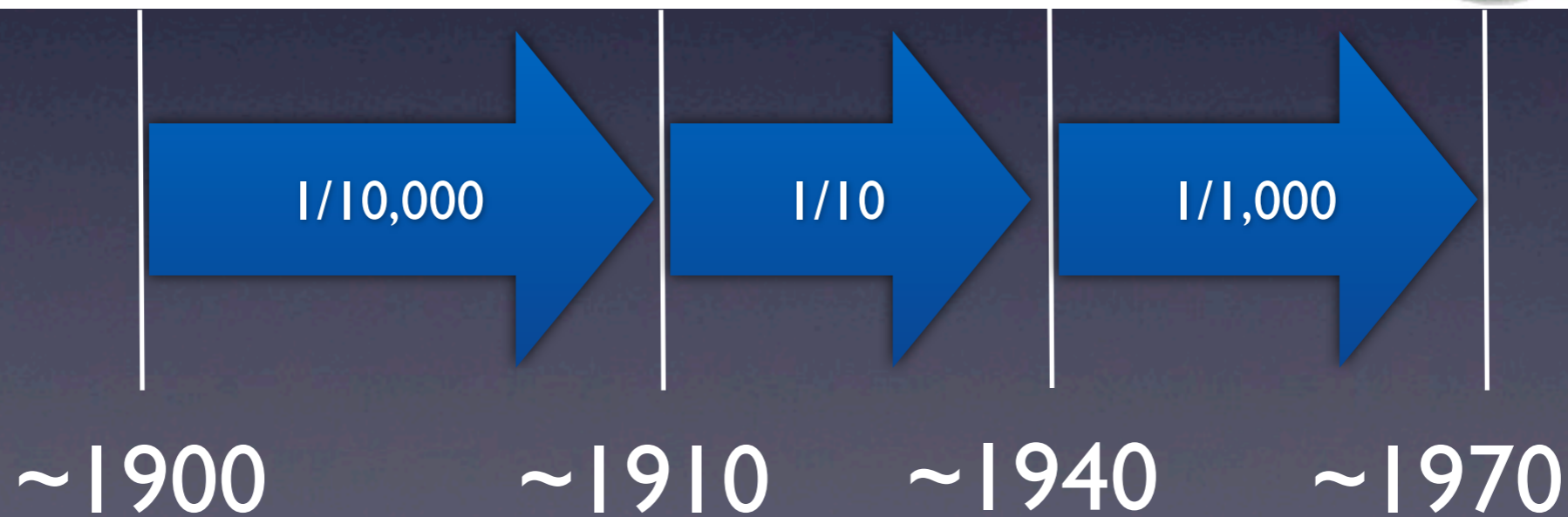
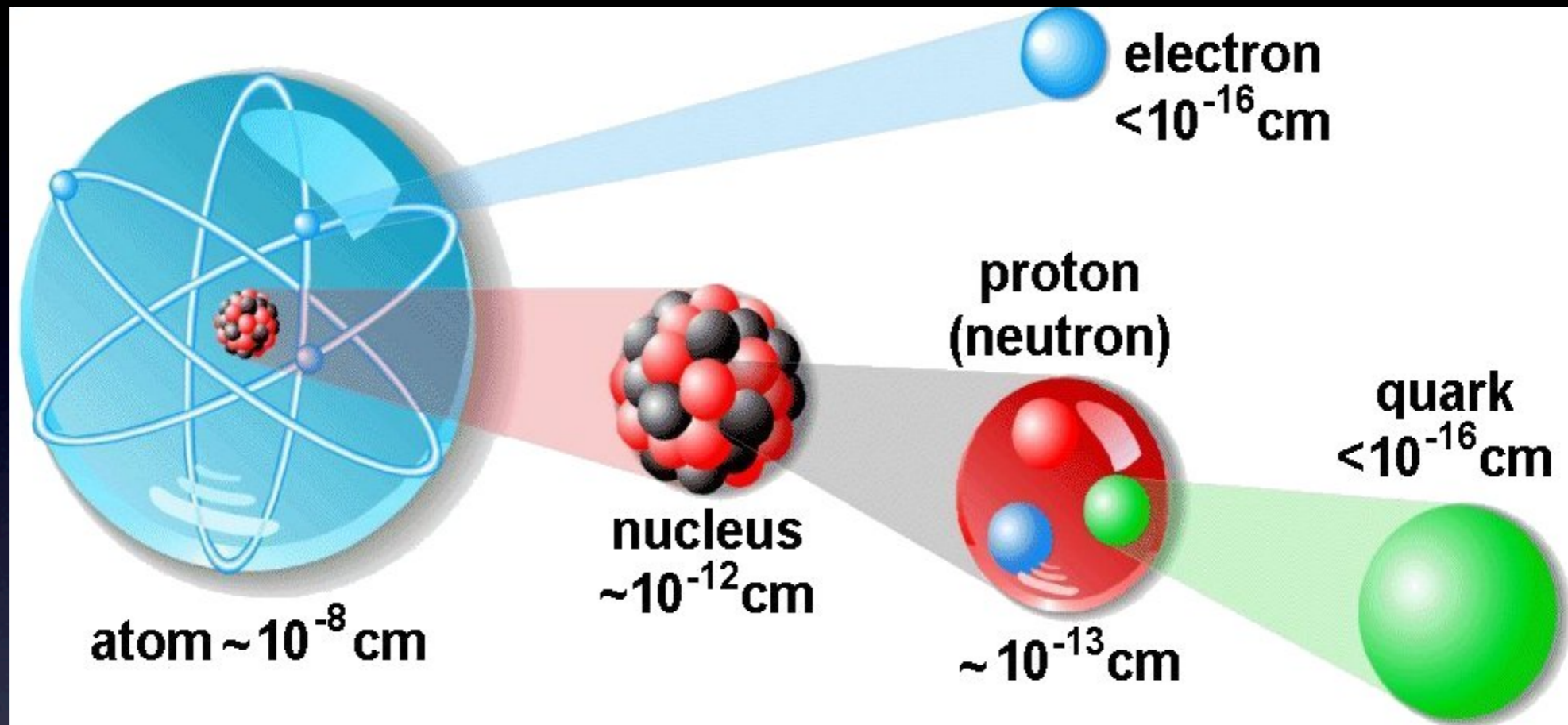
The 20th Century



The 20th Century



The (later) 20th Century



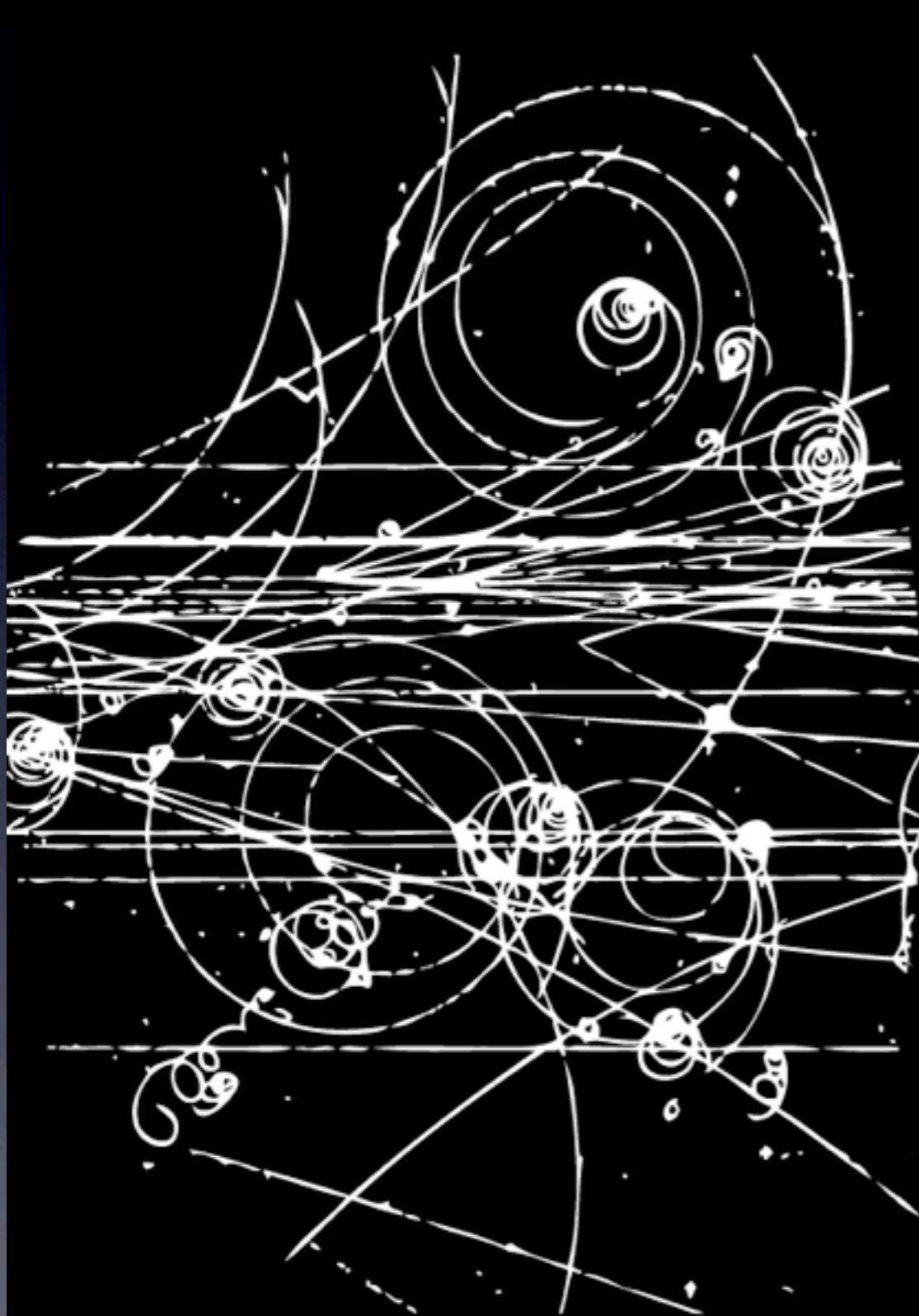
An aside on units

- Particle physicists use “natural units”
 - $c = \hbar = 1$
- Can write mass/distance/time in units of energy
 - $1 \text{ eV}/[c^2] = 1.8 \times 10^{-36} \text{ kg}$
 - $m_{\text{proton}} = 938 \text{ MeV}, m_{\text{electron}} = 0.511 \text{ MeV}$

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The particle zoo (1940s-50s)



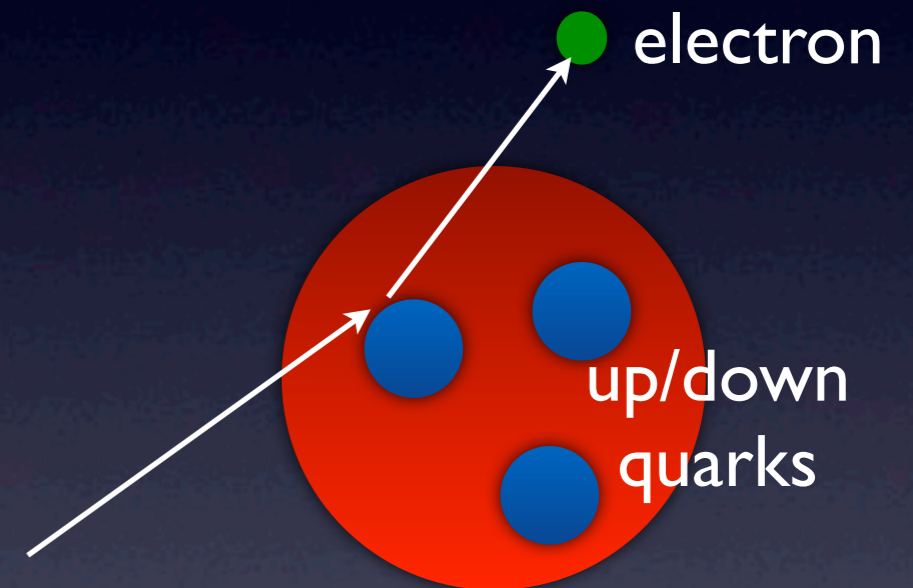
- Accelerator-based particle physics flourishes
- Dozens of “fundamental” particles discovered
- Picture starts to look complex
- Are they actually fundamental?

Quarks inside protons/neutrons



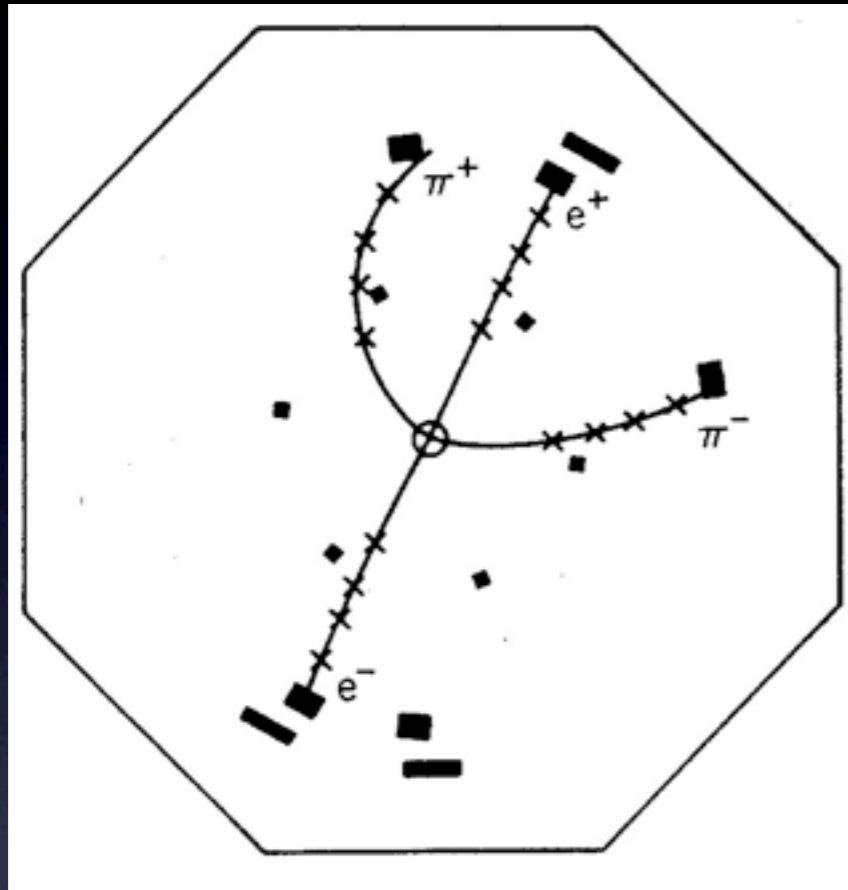
Stanford Linear Accelerator Center
1969

Accelerate electrons
into atomic nuclei

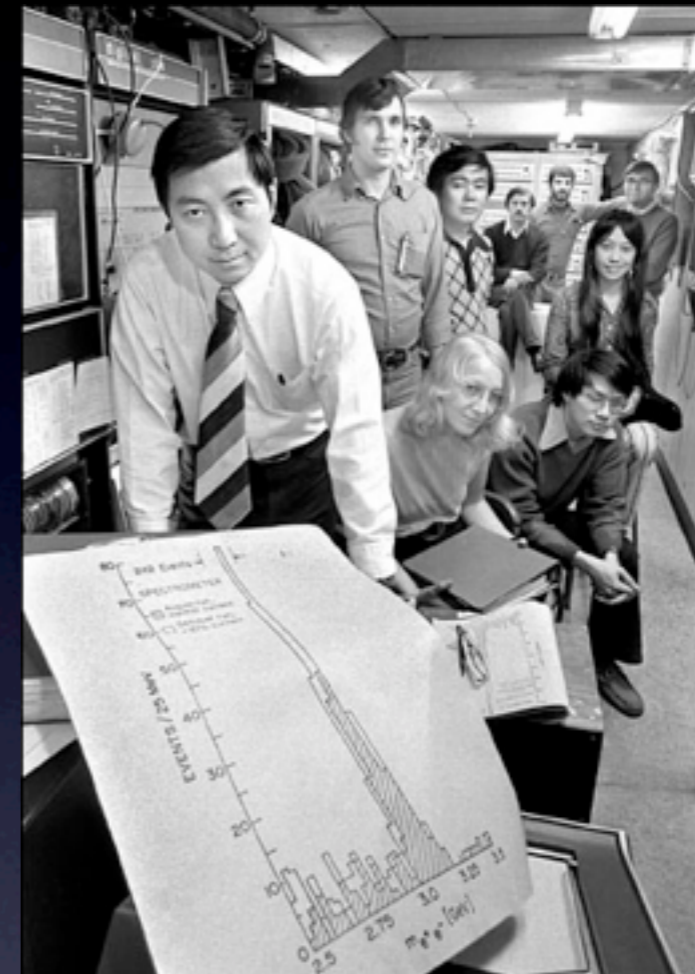


At rest:
proton ($2u+1d$)
neutron ($2d+1u$)

Discovery of charm[ed] mesons



B. Richter, et al. (SLAC)
“ ψ ” particle



S. Ting, et al. (BNL)
“J” particle

J/ψ meson
Nobel Prize (1974)

Discovery of W and Z bosons



Super Proton Synchrotron (SPS)
proton-antiproton collider: 630 GeV

CERN (Geneva, Switzerland)

Standard model predicts
large masses for W and Z
bosons (~ 80 GeV)

UA1 and UA2 experiments
announce discovery in 1983

C. Rubbia and S. Van der
Meer: Nobel Prize (1984)



PRESSE

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

(a complement to PR 02/83
dated 21 January 1983)

PR 03/83
25.01.1983

A MAJOR STEP FORWARD IN PHYSICS :

THE DISCOVERY OF THE W VECTOR BOSON